The plan:

Neutrinos Now...

Neutrinos Next:

- Neutrinos and the New Paradigm
- Neutrinos and the Unexpected Today
- Neutrinos and the Cosmos Today

Neutrino Opportunities Today

Neutrinos and the Unexpected

un•ex•pect•ed *(adj.)*

Not regarded as likely to happen.

But if it did... it would knock your socks off.

"Most likely, the solar neutrino problem has nothing to do with particle physics..."

Howard Georgi, 1990

⇒ History says it is wise
to be open to the unexpected!

If “the unexpected” is an experimental signature,

it usually starts out with low significance --

New physics is discovered on fluctuations upward.

Initial 2-3σ with Positive resolution

- J/ψ (charm) shoulder at Brookhaven
- Tau lepton at SLAC
- Solar neutrino oscillations
- CP violation in the K system

……………………..

Initial 2-3σ with Negative resolution

- Mono-jets at CERN Collider
- 17 keV neutrino
- g-2 discrepancy with theory
- pentaquarks

………………………..

THOSE WHICH PROVED TRUE HAVE CHANGED OUR FIELD.

The trick is to pick the right ones.

When an anomaly is found, it might be...

1. A statistical fluctuation (possibly enhanced by cuts)
2. A systematic effect
3. Something real

Anomalies should be regarded with healthy skepticism

but also healthy care!

Don't reject out of hand.

Think it through

Talk to the authors ← This is <u>very</u> important

If it passes your "quality tests,"

then you should pursue the question...

But be prepared for the fact that
most people will
think you’re nuts.

What do you care what other people think?

For this discussion...

Two existing of anomalies I find interesting
(with a $>3\sigma$ criteria)

- LSND
- The number of neutrinos (LEP/NuTeV)

And a property we really should investigate further:

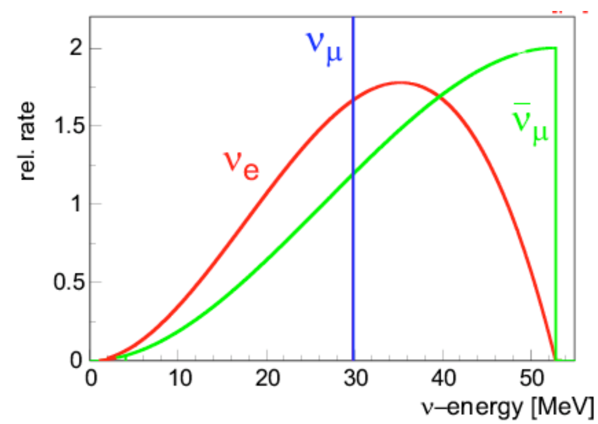
- Neutrino Magnetic Moments

LSND: A 4σ excess of ν_e in a ν_μ beam

The LSND Experiment at LANL (1993-1998)

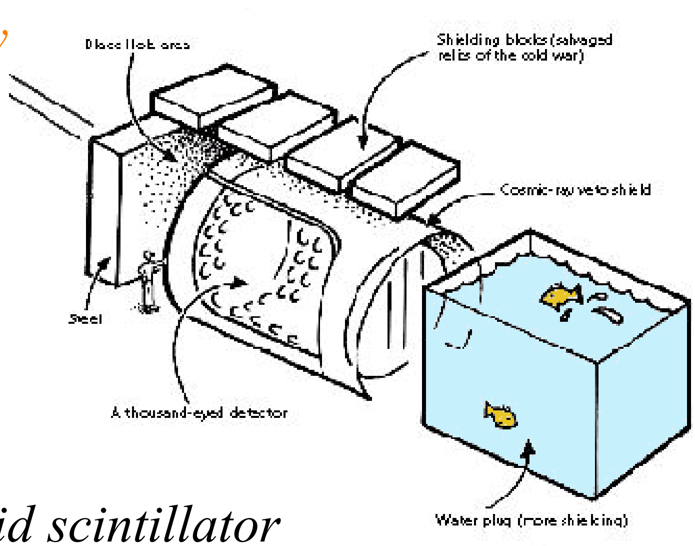
Nearly 49,000 Coulombs of protons on upstream target

Beam from stopped muon decay



Neutrino Energy 20-55 MeV,

Baseline 30 m



167 tons Liquid scintillator

1220 phototubes

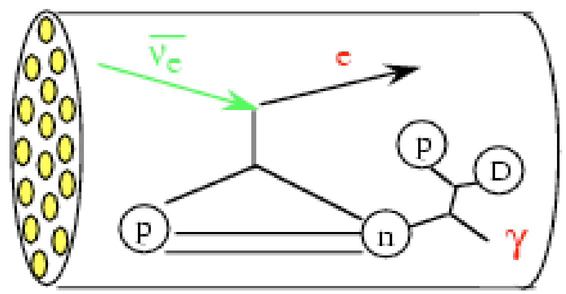
The anti-electron neutrino rate is 1E-4 lower than the other sources

So this is ideal for looking for

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

if $\bar{\nu}_\mu \to \bar{\nu}_e$...

$$\bar{\nu}_e + p \to e^+ + n$$
$$n + p \to d + \gamma(2.2\text{MeV})$$



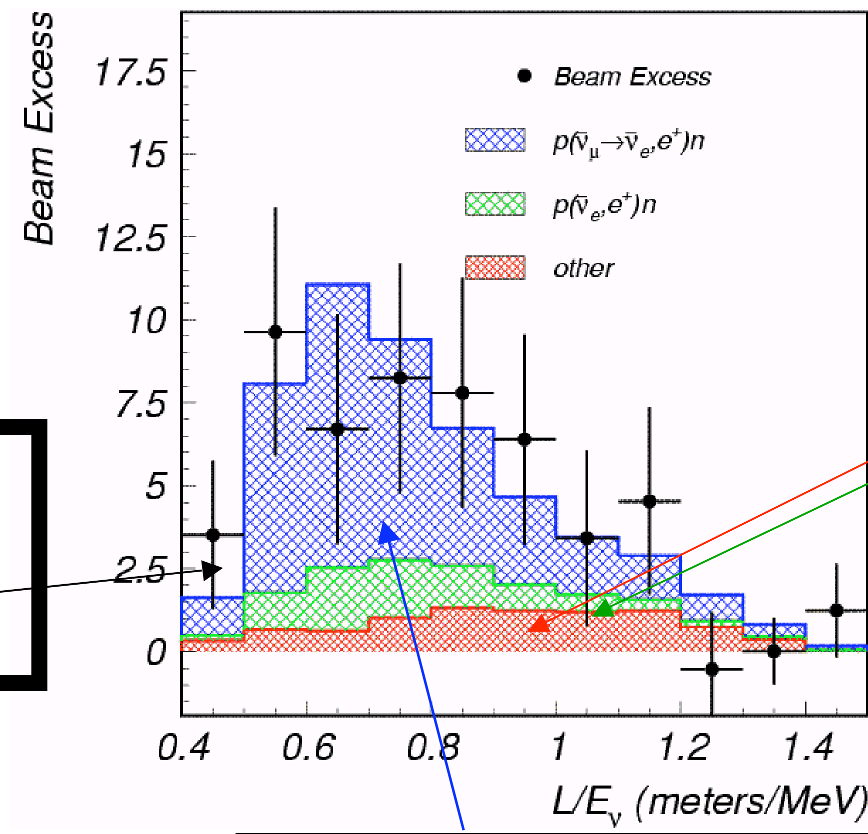
Recall that a signal appears for

$$\Delta m^2 L/E \sim 1$$

L = 30 m
E = 30 MeV $\Rightarrow$ $\Delta m^2 \sim 1\ \text{eV}^2$

And an anti-electron neutrino signal was observed:

$87.9 \pm 22.4 \pm 6.0$ (4.σ)

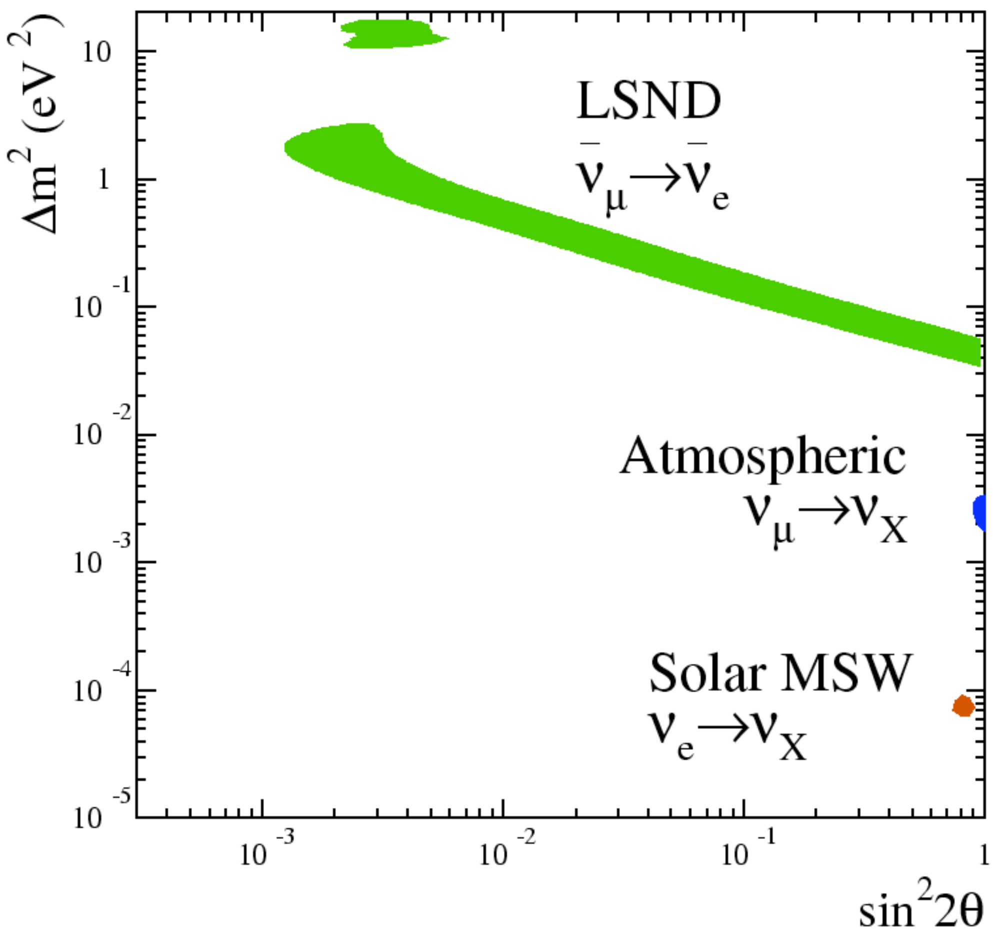


Data points: Excess after Beam-off subtraction

Size of the Beam-related backgrounds

Expectation for oscillations ($\Delta m^2=0.24$ eV^2)

Why isn't this just what we are looking for?



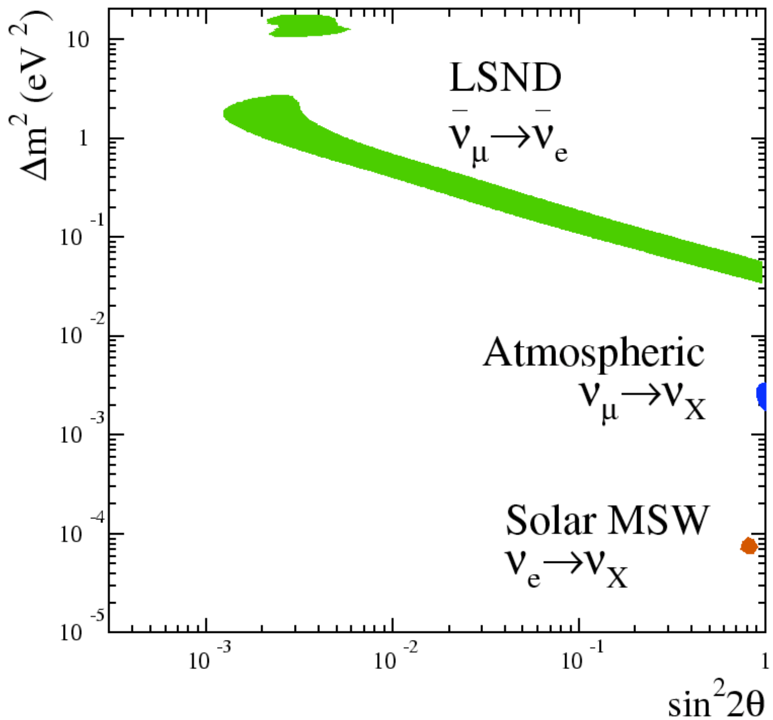
This signal looks very different from the others...

- Much higher Δm^2
- Much smaller mixing angle
- Only one experiment!

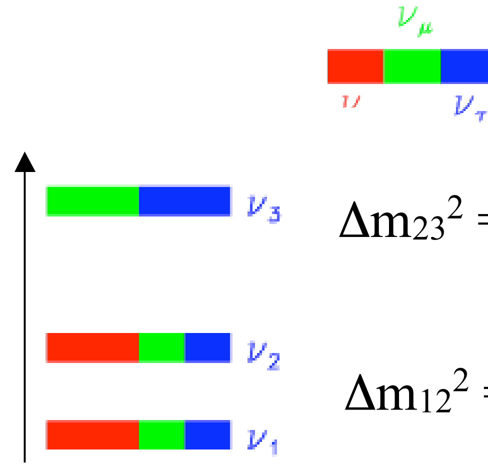
Kamioka, IMB, Super K, Soudan II Macro, K2K

Homestake, Sage, Gallex, Super-K SNO, Kamland

In SM there are only 3 neutrinos



increasing
$(\text{mass})^2$



$\Delta m_{23}^2 = m_2^2 - m_3^2$

$\Delta m_{12}^2 = m_1^2 - m_2^2$

And ... $\Delta m_{13}^2 \; = \; \Delta m_{12}^2 \; + \; \Delta m_{23}^2$

But ... $1 \; \neq \; 0.003 + 0.00005$

LSND | atmos-pheric | solar

A little simplistic
(you should really apply the full 3 neutrino formalism)
but you get the point

LSND may be...

A. A statistical fluctuation
B. Due to systematics
C. A real effect.

If the answer is C,
then we need to find a way to accommodate it.

Sterile Neutrinos

e.g., Sorel, et al, hep-ph/0305255

Mass Varying Neutrinos

e.g., Kaplan, et al, hep-ph/0401099

Lorentz Invariance Violation

e.g., Kostelecky, et al, hep-ph/0406255

Neutrinos & Extra Dimensions

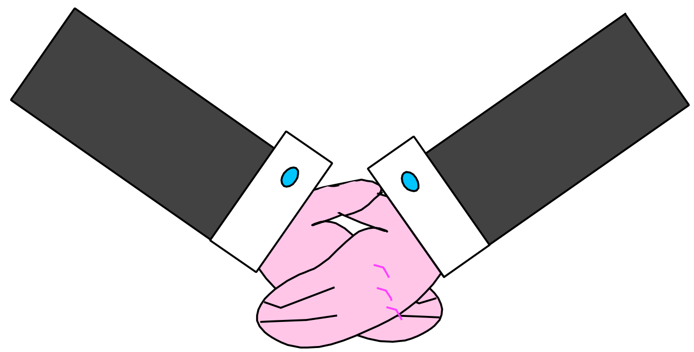
e.g., Pas, et al, hep-ph/0504096

String theories implying Light Dirac Neutrinos

e.g., Giedt, et al, hep-ph/0502032

Sterile Neutrinos, 101

Recall:
"The W only shakes
with the left hand"

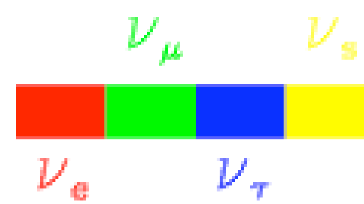


In principle there could be right-handed neutrinos. They just would not interact

"Sterile Neutrinos"

Not in the Standard Model!

...but these can participate in oscillations
if they mix with the active neutrinos



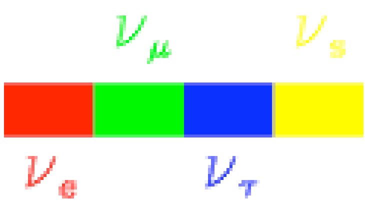
But wait!

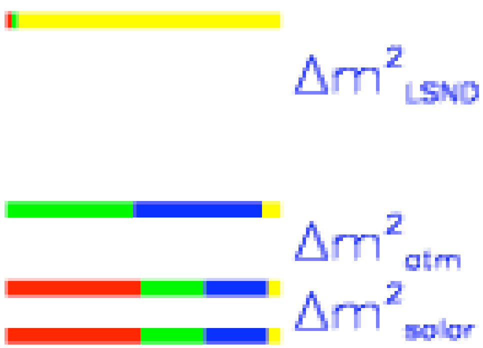
LSND is an oscillation between two active flavors:

$$\nu_\mu \rightarrow \nu_e$$

How does a non-interacting neutrino help?

Remember: the mass states are *mixtures* of the flavor states:





One sterile neutrino is the most conservative

Three sterile neutrinos fits the picture of
"Everything in sets of three"

Two sterile neutrinos fits the data just right
(not enough data to constrain three)

The mixing matrix is 5×5

3+2

active sterile

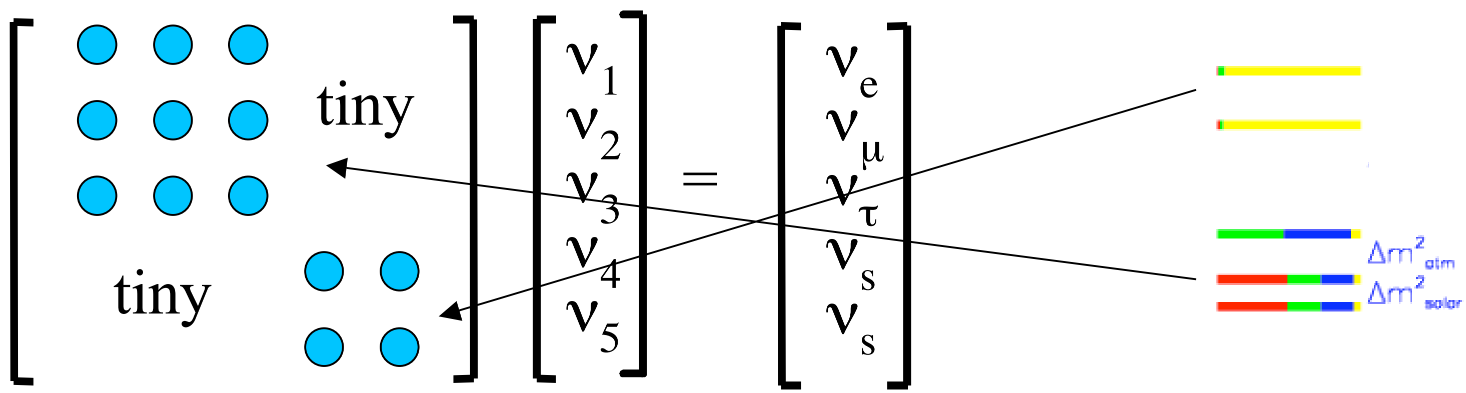
Sorel
Conrad & Shaevitz
PRD 12 Oct 2004

$$\begin{bmatrix} \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \end{bmatrix} = \begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_s \end{bmatrix}$$

As always: **guessing the matrix elements is very hard!**

Include limits ~90% CL on sterile neutrinos from
atmospheric < 30%
solar < 10%

There are 3 neutrinos that have very little sterile content...

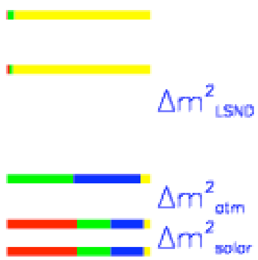


Somewhat smaller space to explore,
But still requires a scan using a computer farm

The experiments with high sensitivity to the sterile neutrinos will be those with sensitivity to large Δm^2...

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

Short baseline experiments



Channel	Experiment	Lowest Δm^2 Reach (90% CL)	$\sin^2 2\theta$ Constraint (90% CL) High Δm^2	Optimal Δm^2
$\nu_\mu \to \nu_e$	LSND	$3 \cdot 10^{-2}$	$> 2.5 \cdot 10^{-3}$	$> 1.2 \cdot 10^{-3}$
	KARMEN	$6 \cdot 10^{-2}$	$< 1.7 \cdot 10^{-3}$	$< 1.0 \cdot 10^{-3}$
	NOMAD	$4 \cdot 10^{-1}$	$< 1.4 \cdot 10^{-3}$	$< 1.0 \cdot 10^{-3}$
$\nu_e \to \nu_{\not e}$	Bugey	$1 \cdot 10^{-2}$	$< 1.4 \cdot 10^{-1}$	$< 1.3 \cdot 10^{-2}$
	CHOOZ	$7 \cdot 10^{-4}$	$< 1.0 \cdot 10^{-1}$	$< 5 \cdot 10^{-2}$
$\nu_\mu \to \nu_{\not\mu}$	CCFR84	$6 \cdot 10^{0}$	none	$< 2 \cdot 10^{-1}$
	CDHS	$3 \cdot 10^{-1}$	none	$< 5.3 \cdot 10^{-1}$
$\nu_\mu \to \nu_\tau$	NOMAD	$7 \cdot 10^{-1}$	$< 3.3 \cdot 10^{-4}$	$< 2.5 \cdot 10^{-4}$
	CHORUS	$5 \cdot 10^{-1}$	$< 6.8 \cdot 10^{-4}$	$< 4.5 \cdot 10^{-4}$
$\nu_e \to \nu_\tau$	NOMAD	$6 \cdot 10^{0}$	$< 1.5 \cdot 10^{-2}$	$< 1.1 \cdot 10^{-2}$
	CHORUS	$7 \cdot 10^{0}$	$< 5.1 \cdot 10^{-2}$	$< 4 \cdot 10^{-2}$

Look for oscillation to steriles directly (disappearance)

Or probe that very small probability for transition between active flavors

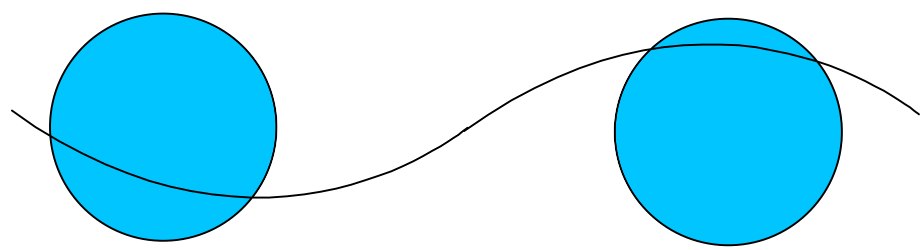
Experiments which pull the result
(in descending order of significance)

LSND has a 4σ appearance signal

Two "Null Experiments" with ~2σ effects that cause a pull:

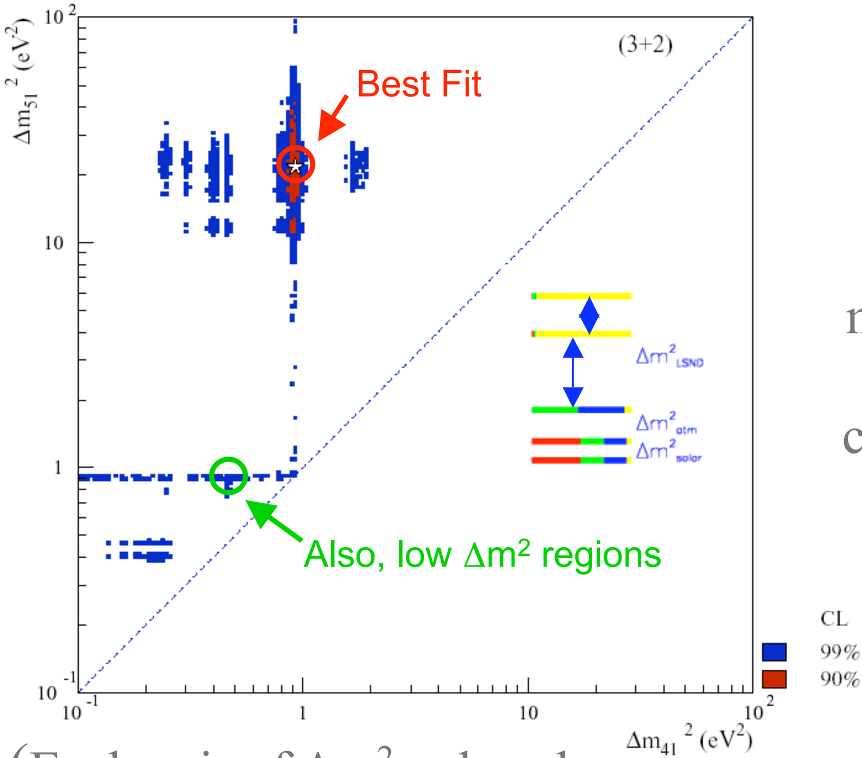
CDHS could see ν_μ disappearance using

a near detector a far detector



What they saw was less beam at the near than far detector with the right energy dependence for oscillations at...

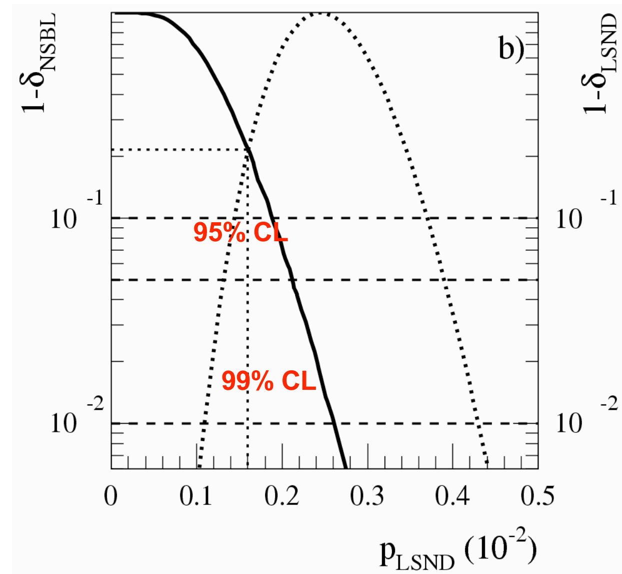
Bugey (reactor) ν_e disappearance in a single detector



(Each pair of Δm^2 values has a range of allowed mixing angle solutions)

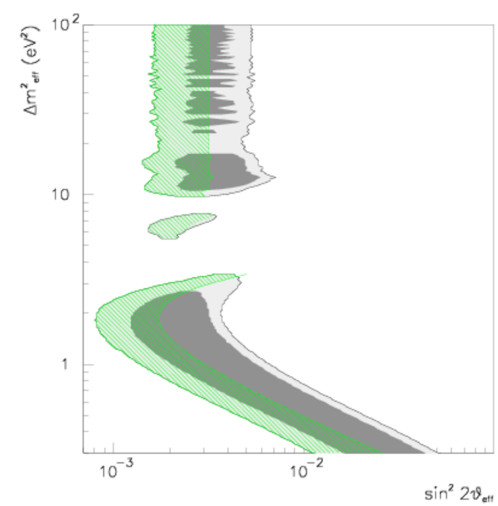
Compatibility Level = 30%

Under this model, there is good compatibility with LSND



Results of the fits

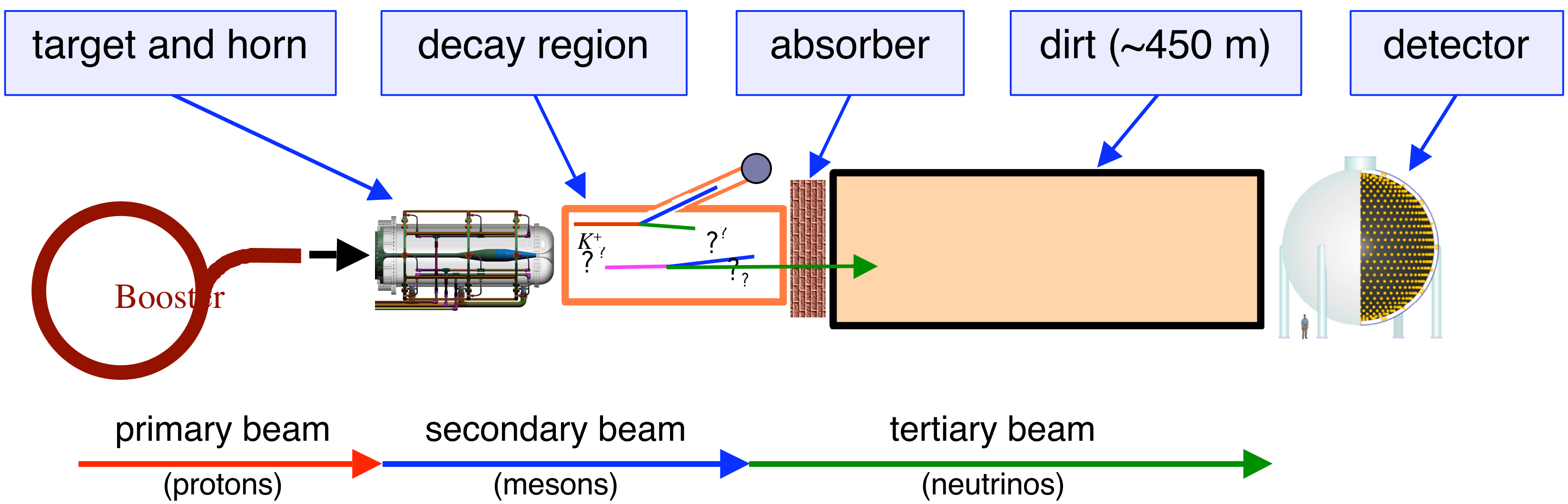
The allowed region in a 3+2 model overlaid on the LSND signal region



How to investigate this?
MiniBooNE:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27\Delta m^2 L/E)$$

Keep L/E same while changing systematics

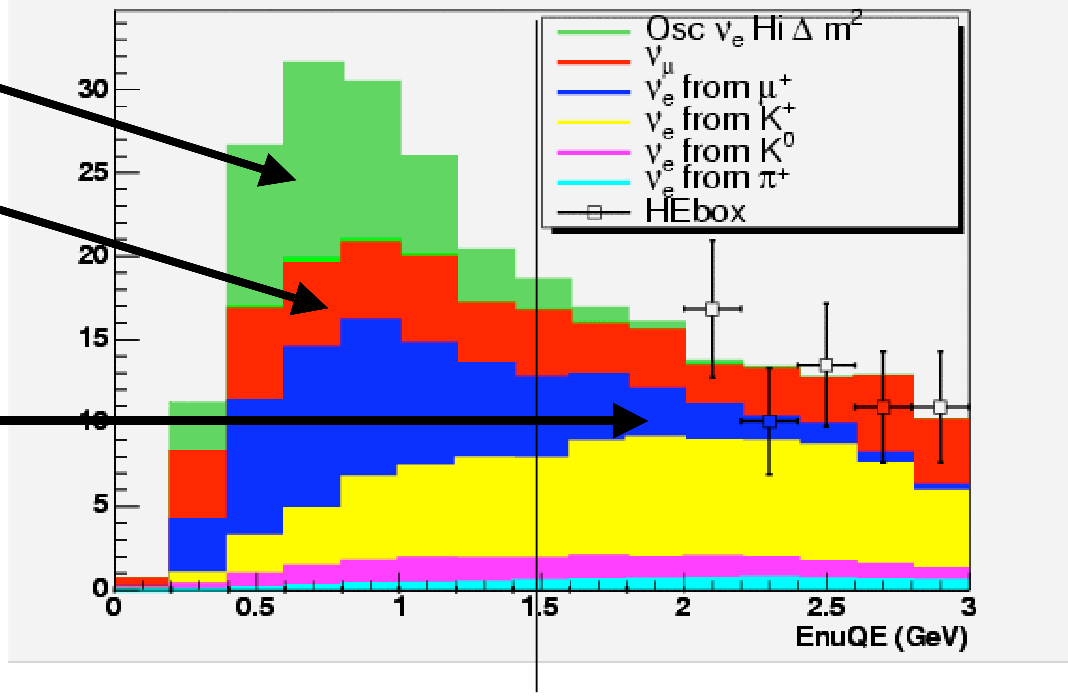


We are looking for this

We are working to reduce these backgrounds

We use this region to constrain our backgrounds

(This is for 1/2 of data set)



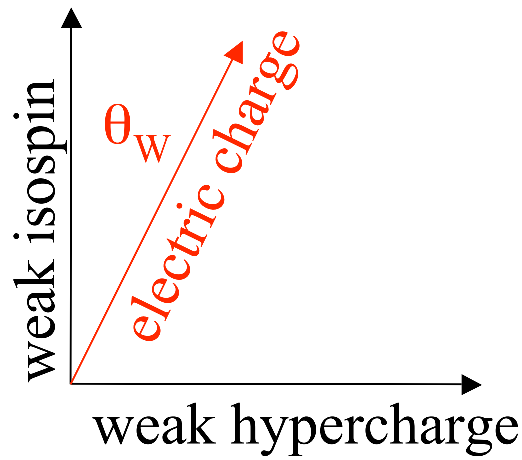
We are working toward opening "the box" soon

NuTeV/LEP: How Many Neutrinos?

The Weak Mixing Angle

SU(3) × SU(2) × U(1)

Parameterizes the mixing between Z_{weak} and γ in the electroweak theory



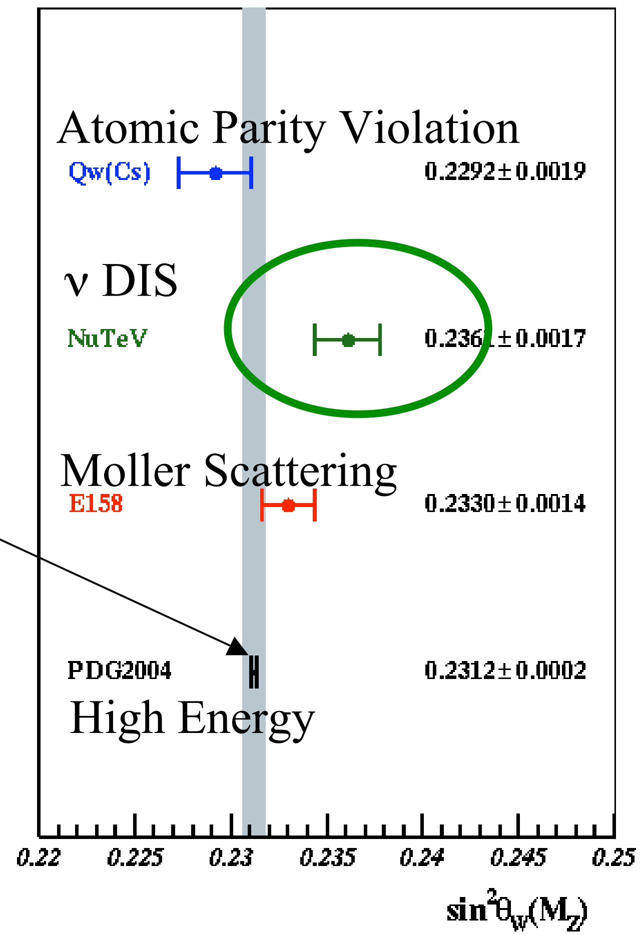
$$\sin^2 \theta_W = 1 - (M_W/M_Z)^2$$

A *fundamental* parameter
accessible in all processes with Z-exchange

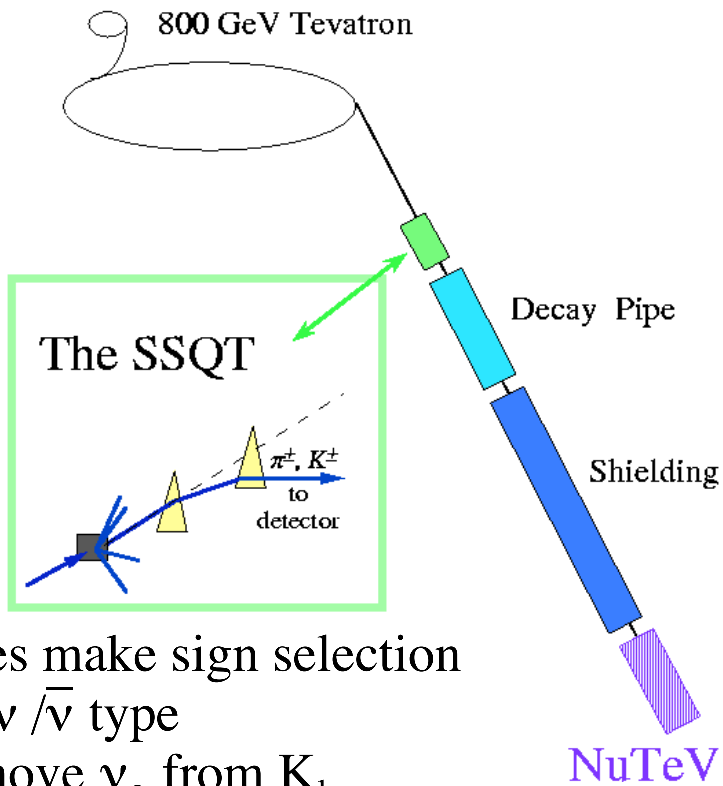
Cross-comparing measurements using many processes...

Agreement constrains the SM...
e.g. the many beautiful measurements from LEP, SLD & TeVatron

Disagreement *may* open a window on new physics



What was NuTeV?

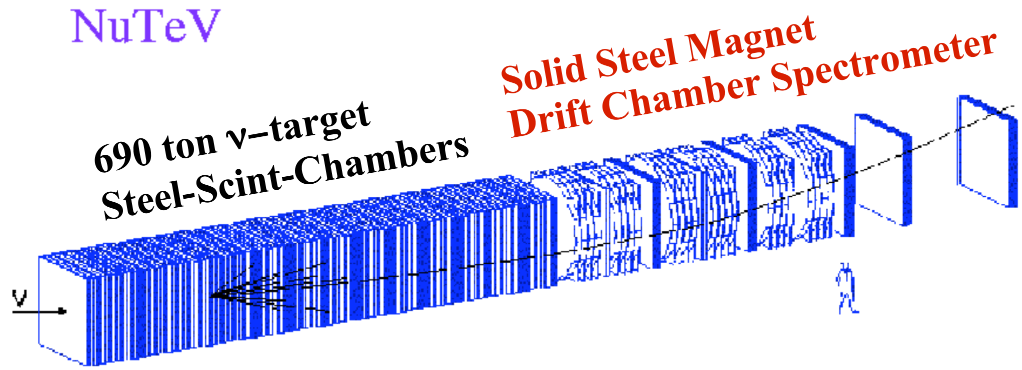


Beam is almost pure ν or $\bar{\nu}$
($\bar{\nu}$ in ν mode 3×10^{-4},
ν in $\bar{\nu}$ mode 4×10^{-3})

Beam only has
~1.6% electron neutrinos
$\Rightarrow$ Important background for isolating true NC event

Dipoles make sign selection
- Set ν / $\bar{\nu}$ type
- Remove ν_e from K_{long}

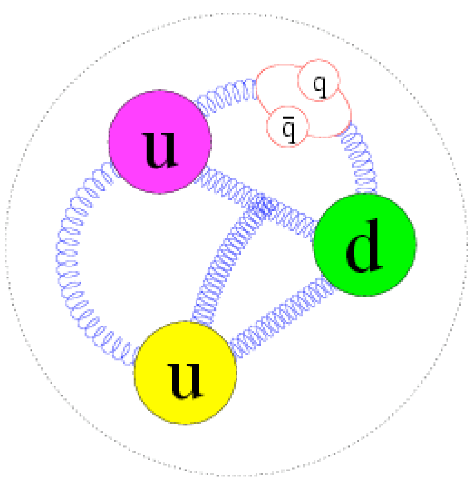
Detector identifies Deep Inelastic Scatters (CC and NC)



A design with separate ν and $\bar{\nu}$ beams lets you measure...

$$R^{-} = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \frac{R^{\nu}\text{-}rR^{\bar{\nu}}}{1\text{-}r} = \_ - \sin^2\theta_W$$

Many systematics cancel...



$d_{sea} - \bar{d}_{sea} = 0$ (only $d_{valence}$ contributes)
$u_{sea} - \bar{u}_{sea} = 0$ (only $_{uvalence}$ contribute)
$s_{sea} - \bar{s}_{sea} = 0$ .... no strange quark contribution
$c_{sea} - \bar{c}_{sea} = 0$ .... no charm quark contribution

Charm production only enters through d_v
which is 1) Cabbibo suppressed and
2) at high x
→ charm mass uncertainty is small

Result...

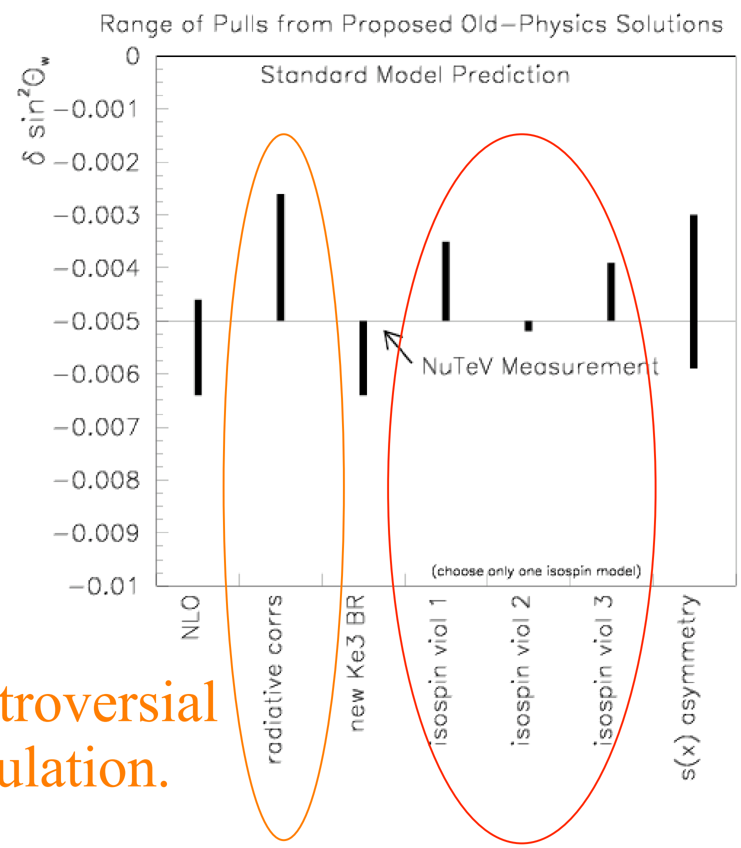
SOURCE OF UNCERTAINTY	$\delta\sin^2\theta_W$	$\delta R^{\nu}_{\mathrm{exp}}$	$\delta R^{\overline{\nu}}_{\mathrm{exp}}$
Data Statistics	0.00135	0.00069	0.00159
Monte Carlo Statistics	0.00010	0.00006	0.00010
TOTAL STATISTICS	0.00135	0.00069	0.00159
$\nu_e, \overline{\nu}_e$ Flux	0.00039	0.00025	0.00044
Interaction Vertex	0.00030	0.00022	0.00017
Shower Length Model	0.00027	0.00021	0.00020
Counter Efficiency, Noise, Size	0.00023	0.00014	0.00006
Energy Measurement	0.00018	0.00015	0.00024
TOTAL EXPERIMENTAL	0.00063	0.00044	0.00057
Charm Production, $s(x)$	0.00047	0.00089	0.00184
R_L	0.00032	0.00045	0.00101
$\sigma^{\overline{\nu}}/\sigma^{\nu}$	0.00022	0.00007	0.00026
Higher Twist	0.00014	0.00012	0.00013
Radiative Corrections	0.00011	0.00005	0.00006
Charm Sea	0.00010	0.00005	0.00004
Non-Isoscalar Target	0.00005	0.00004	0.00004
TOTAL MODEL	0.00064	0.00101	0.00212
TOTAL UNCERTAINTY	0.00162	0.00130	0.00272

What NuTeV worried about as experimentalists

What has been questioned by others in trying to explain the anomaly

"Standard Model Explanations"

- Upgrade to a full NLO analysis
- Improve radiative corrections
- Update old Ke3 branching ratio
  based on KTeV result
- Isospin symmetry is violated?
  ($u^p \neq d^n$ and $u^n \neq d^p$)
- An s vs $\bar{s}$ sea quark asymmetry?

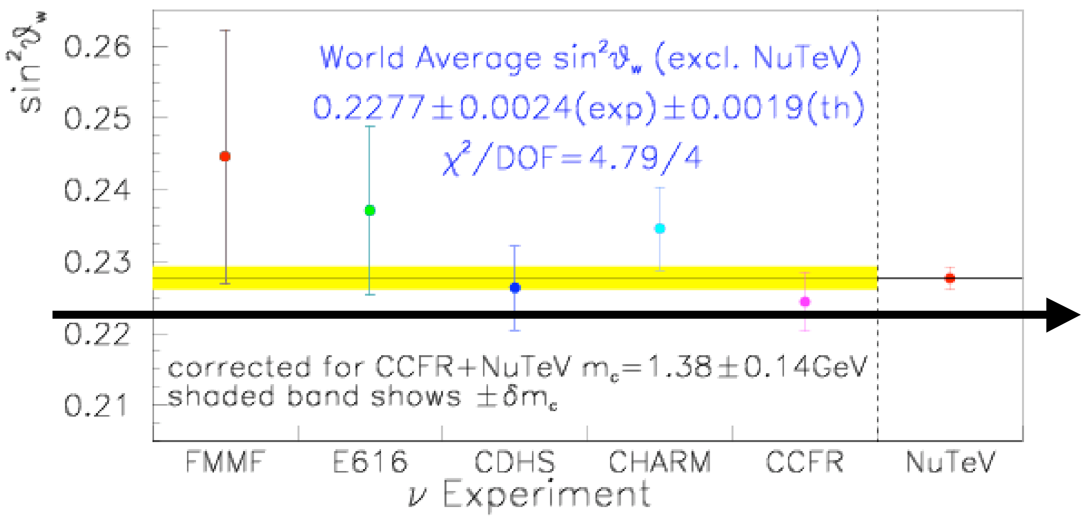


Controversial calculation.

These 3 models are mutually exclusive

Some pull one way, some the other...
No "smoking gun"

Is there an anomaly in the neutrino sector?



PDG "SM"
=0.2227

_ NuTeV is 3σ off the prediction based on LEP & TeVatron
_ Past neutrino DIS experiments show same trend with larger error

One way to interpret this is: The Z doesn't couple to 3 neutrinos,
it effectively couples to fewer.
Why suggest this interpretation...?

LEP I measured the invisible width of the Z:

$$\Gamma_{inv} = \Gamma_{tot} - \Gamma_{had} - \Gamma_{lept} = 499.0 \pm 1.5\text{MeV}$$

You can calculate what that width should be:

$$\Gamma^{SM}(Z \to \nu\bar{\nu}) = 3\Gamma(Z \to \nu_i\bar{\nu}_i) = 3(167.06 \pm 0.22)\text{MeV} = 501.18 \pm 0.66.$$

where $\Gamma(Z \to \nu_i\bar{\nu}_i) = \frac{\sqrt{2}G_F M_Z^3}{24\pi}(2g_A)^2$

The result is...

Γ_{inv} = -2.7 ± 1.6 MeV

Converting this to an effective number of neutrinos:

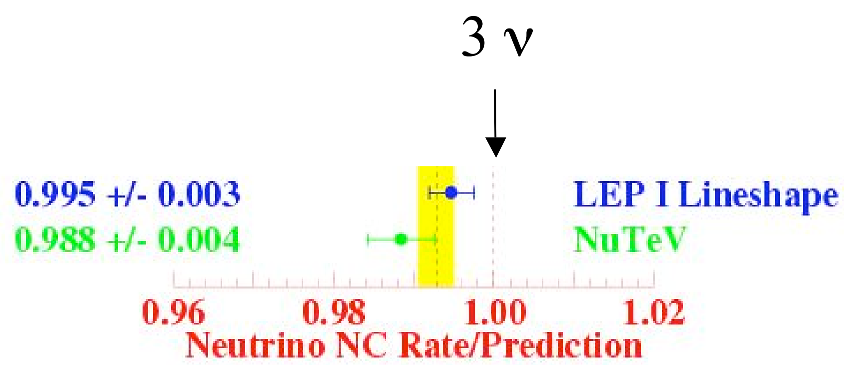
N_ν = 3(0.995 ± 0.003)

i.e. at 1.7σ, the invisible Z line width is too small,

nothing to write home about on its own!

In combination, it's interesting...

Number of neutrinos
assuming SM coupling:
LEP I is 2σ low
NuTeV is 3σ low



$$N_\nu = 3(0.992 \pm 0.002)$$

...4σ in combo

An example
model for this

Loinaz et al., hep-ph/0210193

$Z\nu\nu \leftrightarrow (1-\varepsilon)$
$Wl\nu \leftrightarrow (1-\varepsilon/2)$
$\varepsilon=0.003$

What kind of experimental follow-up is needed?

✓ One that involves neutrinos

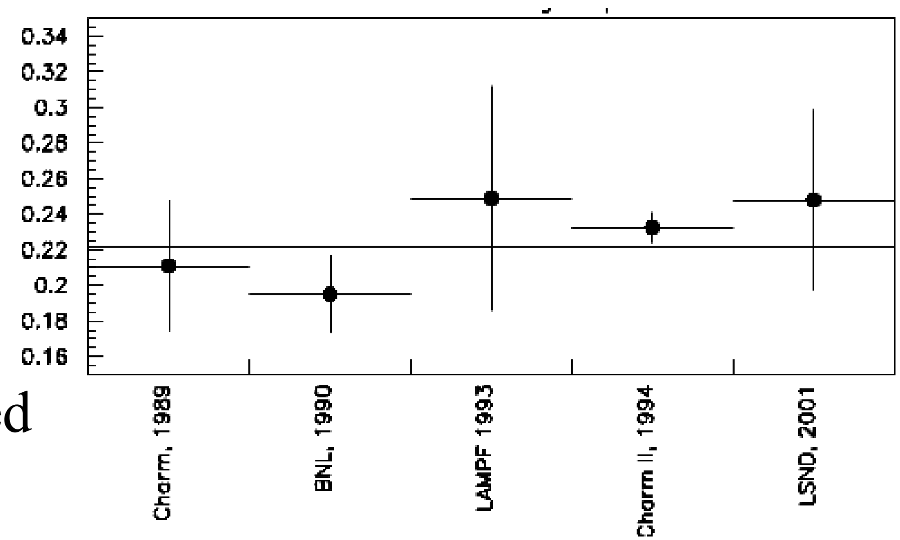
✓ One which escapes the "quark-related" issues of DIS

✓ One with a different radiative corrections

An ideal choice:

νe elastic scattering

νe elastic scattering



line: SM

$\nu_\mu e$ beam-based experiments

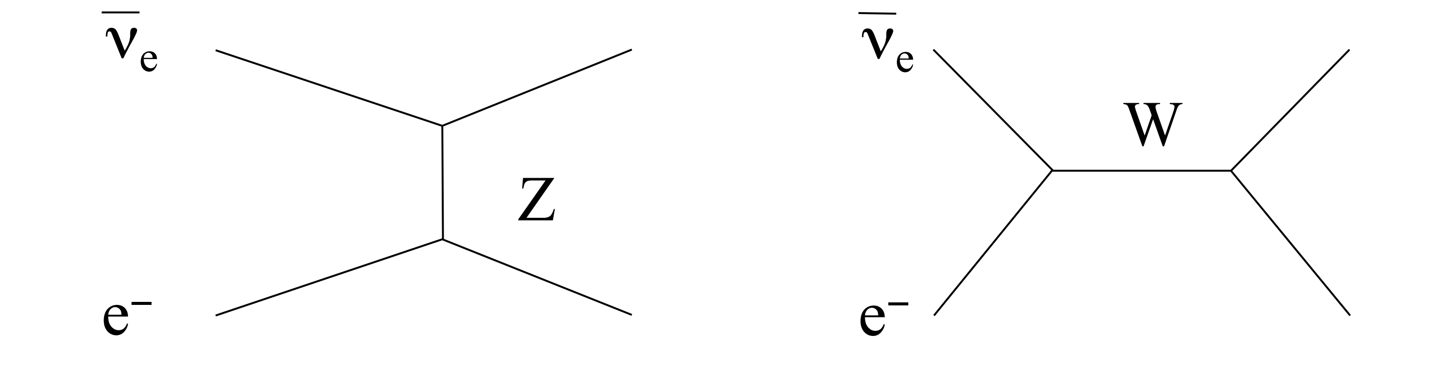
State of the art: Charm II, with errors $\times 5$ larger than NuTeV

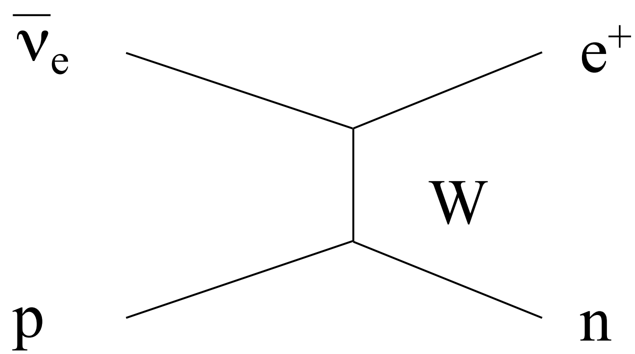
A TeVatron-produced neutrino beam
with a larger “Charm-like” detector could do a beautiful job

But that’s not available.

We may be able to do $\bar{\nu}_e e$ elastic scattering at a reactor

Measure the ratio:





see Conrad, Link, Shaevitz, hep-ex/0403048, PRD71:073013

But this requires simultaneous depth and shielding.
Without Braidwood, we don't have that.

Maybe we should visit the Z-pole
on the way to an ILC?

(There's other physics from this idea also!)

A better way to measure the number of neutrinos extracts

$$e^+e^- \to \nu\,\bar{\nu}\,\gamma$$

From the single photon cross section at the Z resonance

The result from LEP is statistics limited:

$$\Gamma_{inv} = 2 \pm 16 \text{ MeV}$$

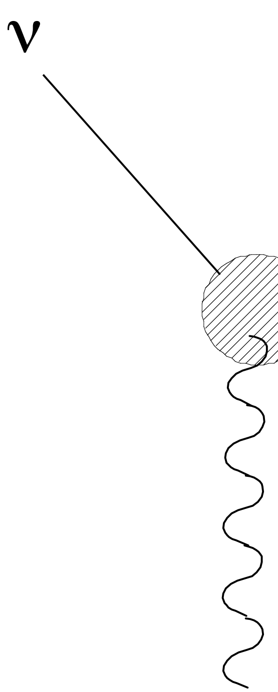
You would need 100× the luminosity to match the
line-shape method

A high luminosity Z factory could be
a great test-bed for ILC technology
(and could even have reusable parts)

Neutrino Magnetic Moments:

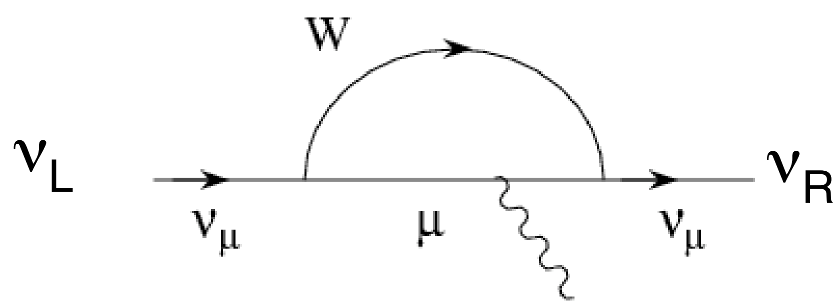
Unexpected is NOT the same as Unpredicted!

Neutrino magnetic moments



A tiny coupling via the γ

Expect a non-zero neutrino magnetic moment if you have massive neutrinos



The signature:
An increase in overall cross section

$$\wp_{tot} = \wp_{weak} + \wp_{EM}$$

Standard model: 10^{-19}

But Beyond-SM theories predict substantially higher values.

There's μ_{ν_e}, μ_{ν_μ}, and μ_{ν_τ}

and μ_1, μ_2, μ_3....

They are combinations of each other...

To know what an experiment can measure,
you need to know the mass state of the beam...

Examples...

- solar ν_e measures μ_2 because the ν_e's exit the Sun in this mass state
- reactor ν_e measures μ_1 and μ_2 because reactors produce ν_e states, which are superpositions of the 1st & 2nd mass states
- accelerator-based experiments measure combos of μ_1, μ_2, and μ_3, depending on the flavor of the beam

Limits set from terrestrial experiments:

Electron neutrino magnetic moment: >1.0 -1.5 10^{-10} μ_B

Preliminary from MUNU (a reactor experiment)

SuperK shape fit (a solar experiment)

Muon neutrino magnetic moment: > 6.8 x 10^{-10} μ_B

LSND experiment

Tau neutrino magnetic moment: >10^{-9} μ_B

The DoNuT Experiment, with a specially designed beam to see ν_τ's

a schematic of donut goes here

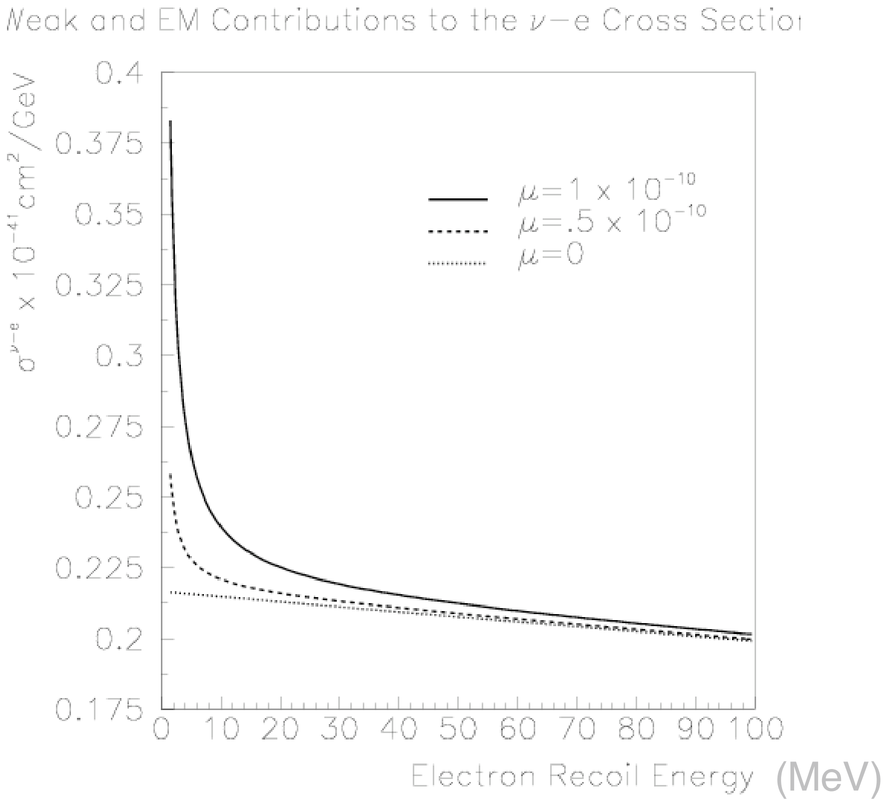
(Limits from astrophysics are flavor-blind but model dependent)

How can we go another order of magnitude or more on μ_{ν_μ}?

$\nu_\mu e$ scattering

$$\frac{d\sigma^{weak}}{dT} = \frac{2m_e G_F^2}{\pi}\left[g_L^2 + g_R^2\left(1-\frac{T}{E_\nu}\right)^2 - \frac{m_e}{E_\nu} g_R g_L \frac{T}{E_\nu}\right]$$

$$\frac{d\sigma^{EM}}{dT} = \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\left(\frac{1}{T}-\frac{1}{E_\nu}\right)$$



Search for a shape change in the differential cross section

Issues:

High intensity-well understood flux,
with timing structure

Large detector with sufficient reconstruction capability

Low levels of radioactive background

Latter two: LAr TPC

With 15,000 events
(5t LAr at 100 m
in the BooNE beamline)

> 6.8 x $10^{-11}\mu_B$

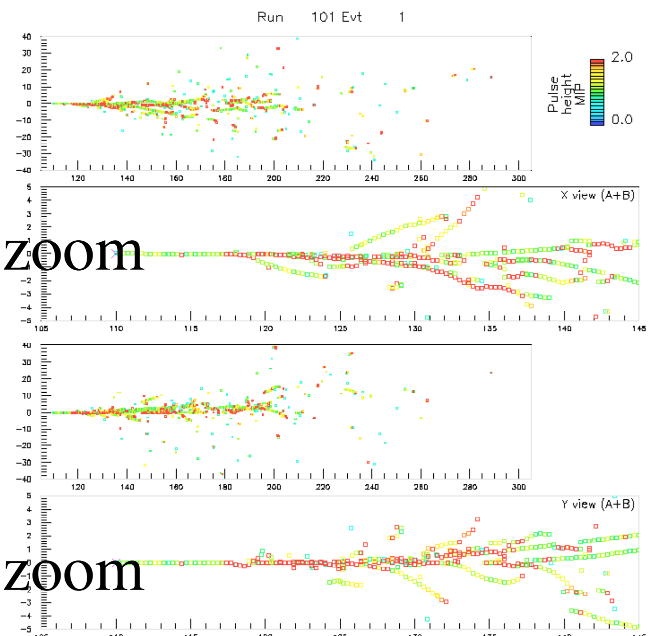
Plus this would be a nice
step to building a large
LAr detector for oscillations

x

x-zoom

y

y-zoom

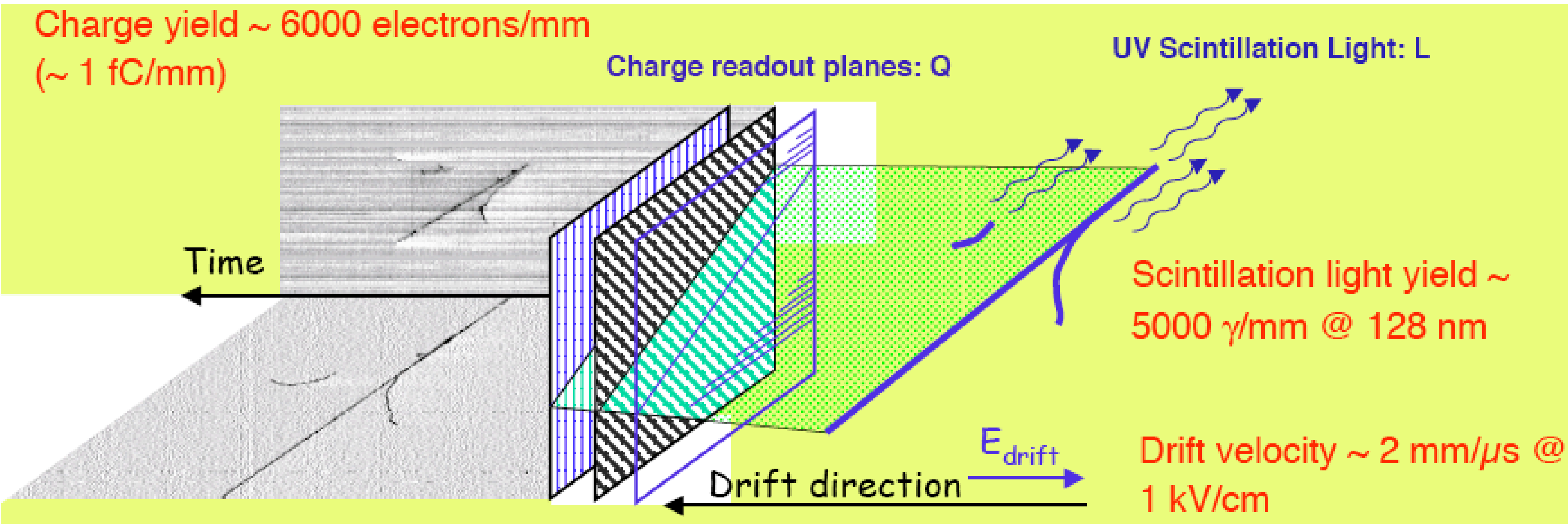


electron event simulation

How does an LAr detector work?

It's a Time Projection Chamber (TPC)

Scintillation light provides the T_0



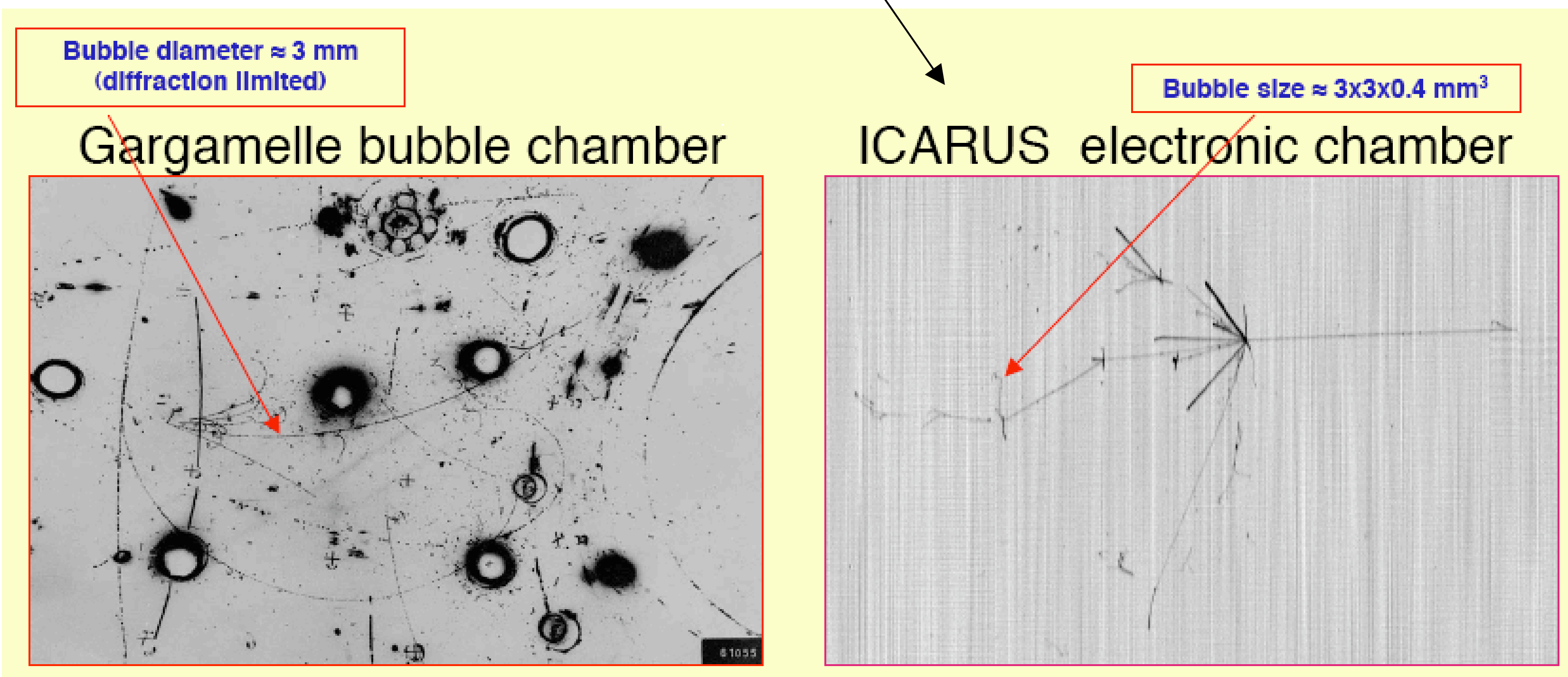
wires detect position in xy plane

drift time is used to get the z coordinate

A REALLY Big REALLY dense TPC...

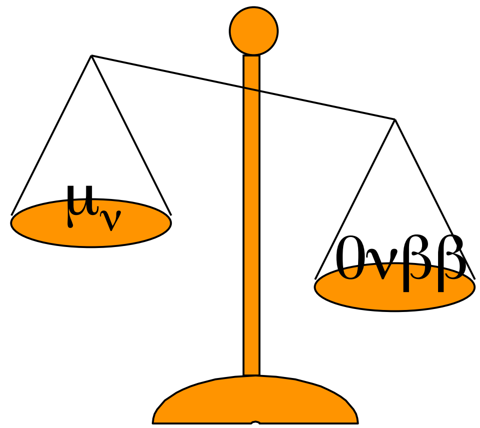
LAr TPC's are cutting edge technology

But there is a working proof-of-principle:
The ICARUS 3-ton detector run at CERN



These were three examples of
"High Risk - High Return" Physics

(others include searches for neutrino decay, mass varying neutrinos, weak coupling to scalar fields, ...)



We wouldn't want a portfolio that is 100% high risk.
But we also don't want to shut doors to new possibilities.

Balancing the unexpected vs. the paradigm-du-jour
is one of the hardest questions for the experimental program.

Neutrinos and the Cosmos

The emerging field of AstroCosmoNuclearParticle Physics

CνB
stars (inc. Sun)
supernovae
atmospheric
AGNs?
Other???

So many sources, so little time!

I'll select:

New aspects of weakly interacting particles that can be learned from astrophysics and cosmology....

...or...

You can't see them, but they're out there

- Sterile neutrinos (revisited)
- Ultra High Energy neutrinos
- Dark Matter

Sterile Neutrinos Revisited

Introducing sterile neutrinos
touches all of AstroCosmoNuclearParticle physics

Particle/nuclear physics • Astrophysics • Cosmology

Brings LSND
into the picture

addresses
uranium abundance
and
pulsar kicks

Relic neutrino
background

Are sterile neutrinos an asset for astrophysics?

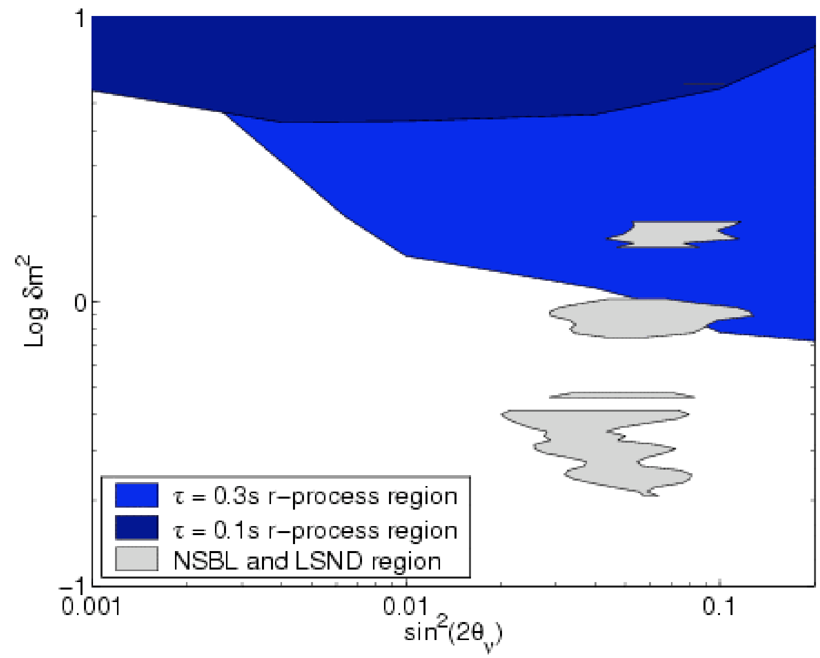
The R-process needs a large neutron imbalance

How do you create a very large neutron-imbalance?
First create an anti-electron neutrino rich environment.

$$\bar{\nu}_e + p \rightleftharpoons e^+ + n,\ \nu_e + n \rightleftharpoons e^- + p$$

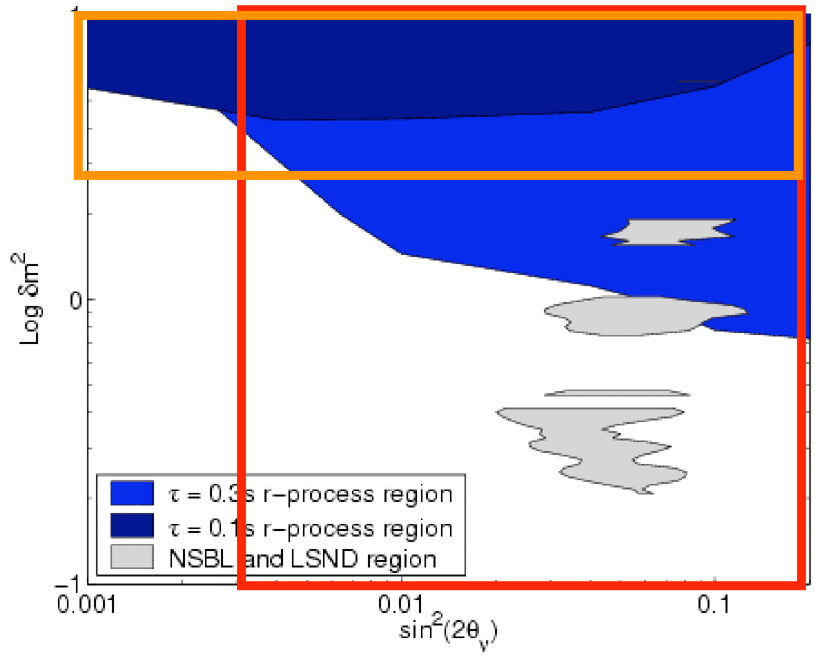
... which works if the conditions are right (high electron density, right oscillation parameters) to produce a $\nu_e \rightarrow \nu_s$ "resonance"

Allowed ranges for oscillation to enable sufficient U production



Beun, Surman, McLaughlin & Hix, preliminary

How to test these parameters?



A short-baseline,
2 detector,
reactor experiment:

E ~ 3 MeV
L ~ 30 m
easily probes down to $\log(\Delta m^2) = -1$
and out to $\sin^2(2\theta)=0.005$

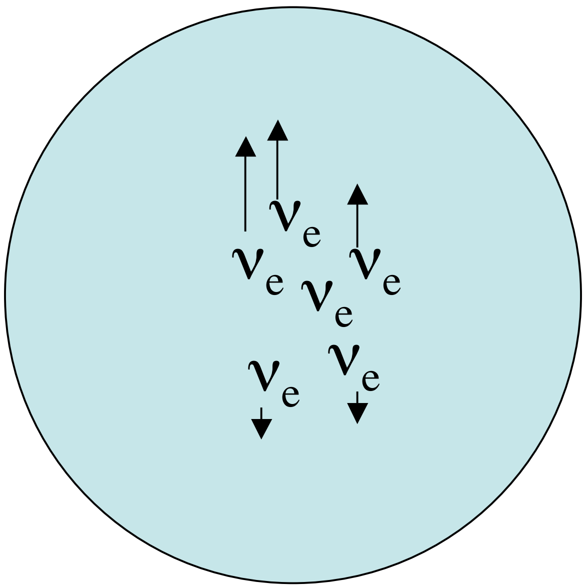
A beta-beam (accelerated nuclei which β-decay)
might be able to reach the upper corner:
E~10 GeV ne
L~ 500 m
if it can be made intense enough

Neither are planned at the moment.

It provides a mechanism for “pulsar kicks”

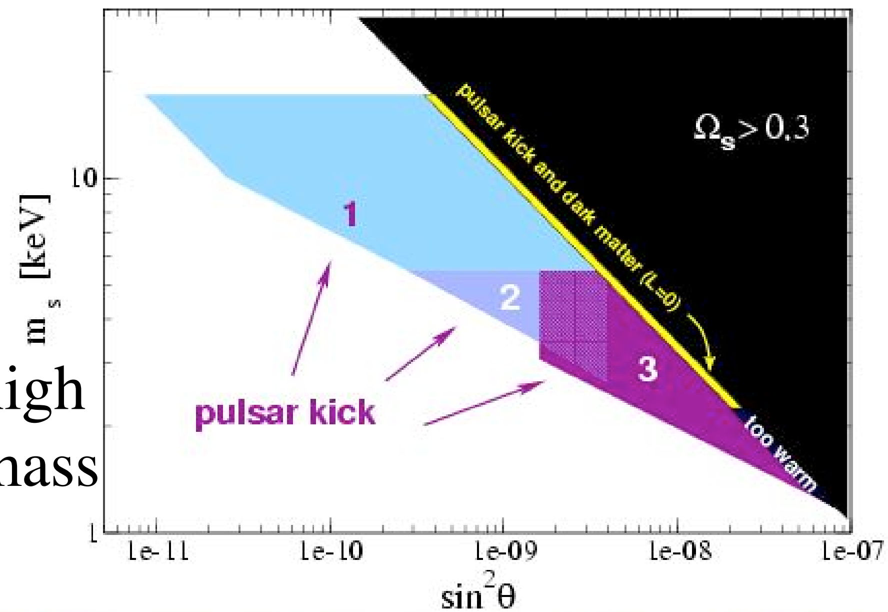
Fuller, Kusenko, Mocioiu, Pascoli, PRD 68, 103002 (2003)

In the supernova,
high magnetic fields
polarize the electrons,
leading to directional scattering



Oscillation to sterile
is needed for escape

high
mass



Tiny mixing

(No chance of reaching in
an earth-based osc exp. now)

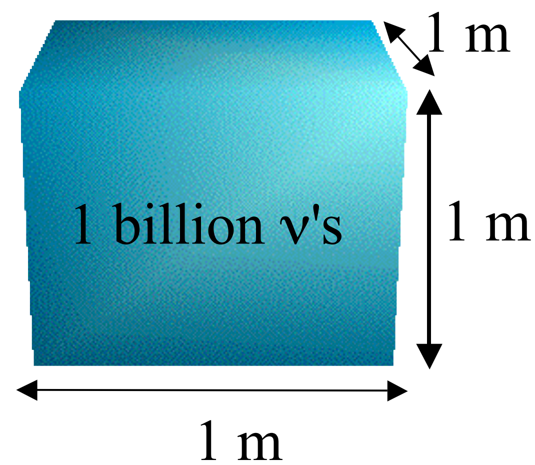
Any extra neutrinos will affect cosmology

Standard Cosmology Assumes

- Only the 3 active neutrino flavors
- Zero neutrino mass
- No neutrino mixings (no oscillations)
- Simple Fermi-Dirac energy distribution (the neutrinos are "thermalized")

number of relic particles of each species testable via:

- expansion rate
- large scale structure



- A small asymmetry in n/p ratio

That will affect:
The D/H ratio
The He abundance
The ^{7}Li abundance

Relic sterile neutrinos affect these predictions!

Option 1: If the neutrinos are not thermalized,
then all bets are off...

Most examples result from couplings to a scalar field...

Majoron models
Acceleron models (MaVaNs)
Extended quintessence
etc.

But there is also:

Low reheating temperature,
A large initial lepton asymmetry
etc.

But why resort to the exotic when....

Option 2: No apologies, no excuses needed...

"New constraints on the cosmological background of relativistic particles," S. Hannestad, astro-ph/0510582

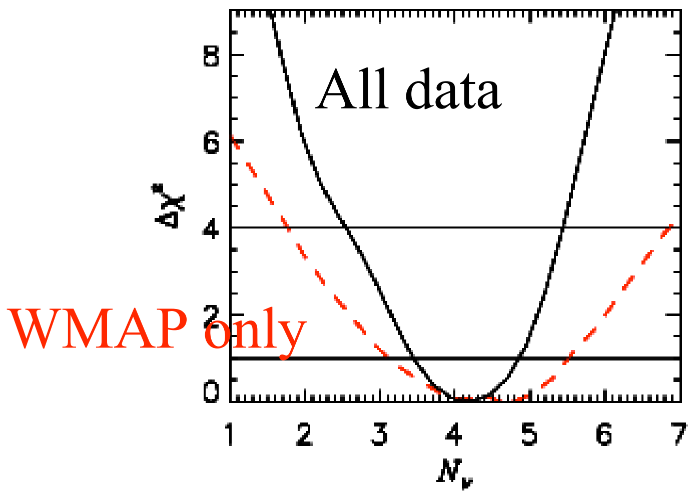
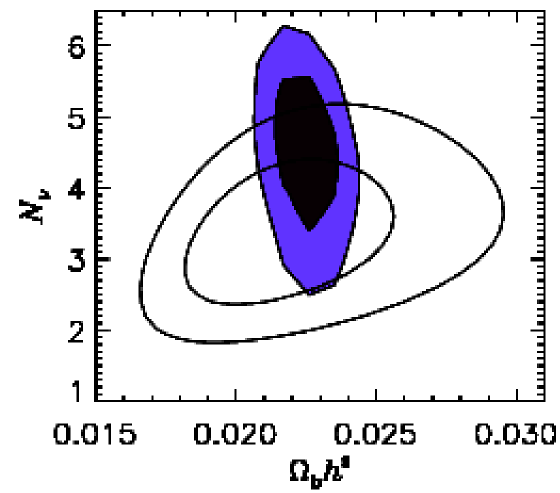


Figure 1. $\Delta\chi^2$ values as a function of N_ν for various data sets. The full line includes all available data, and the dashed line is for WMAP and LSS data only.

Large Scale Structure



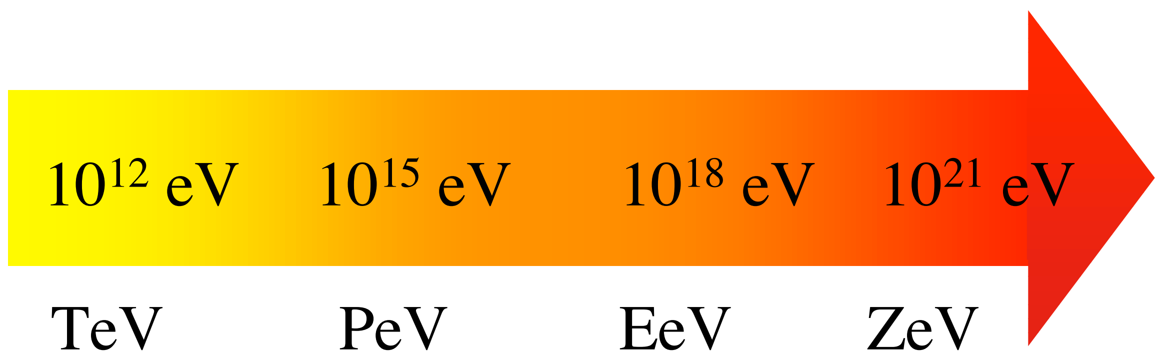
Element abundances from BBN

Figure 2. The 68% (dark) and 95% (light) likelihood contours for $\Omega_b h^2$ and N_ν for all available data. The other contours are 68% and 95% regions for BBN, assuming the ^{4}He and D values given in [39].

$$N_\nu = 4.2\,^{+1.2}_{-1.7}$$

@95% CL

UHE Neutrinos?



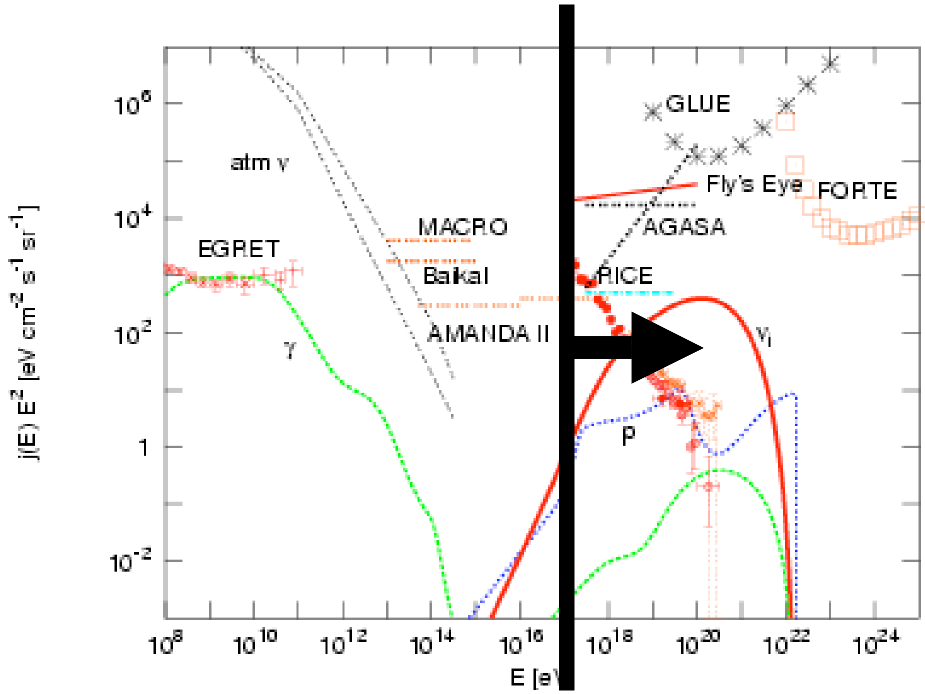
Why UHE Neutrinos?

From the High Energy Physics Point of View:
it's the energy reach!

Experiments that can detect $E_\nu > 10^{17}$ eV are looking well beyond LHC energies!

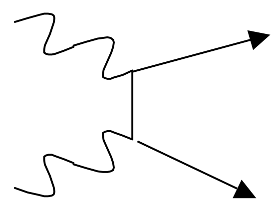
Search for enhancements of $\sigma_{\nu N}$ beyond SM probing...

_ extra dimensions,
_ black hole production,
_ strongly interacting neutrinos,
_ ... *& more exotic stuff!*

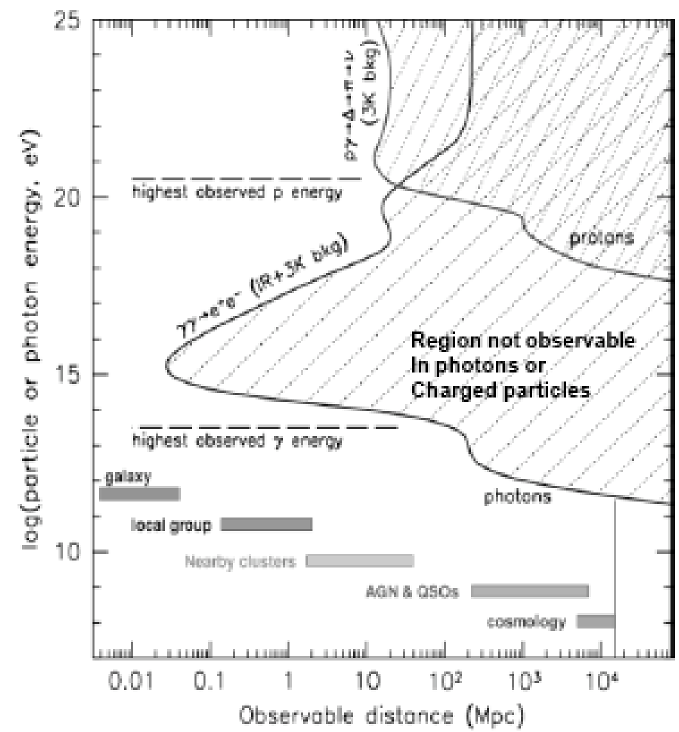


Neutrinos are the only messengers
at > PeV energies!

Photons > 30 TeV are lost to pair production on the CMB



Charged particles
are scattered by B-fields
and range out via the GZK process
(p+CMB → Δ → π+p)

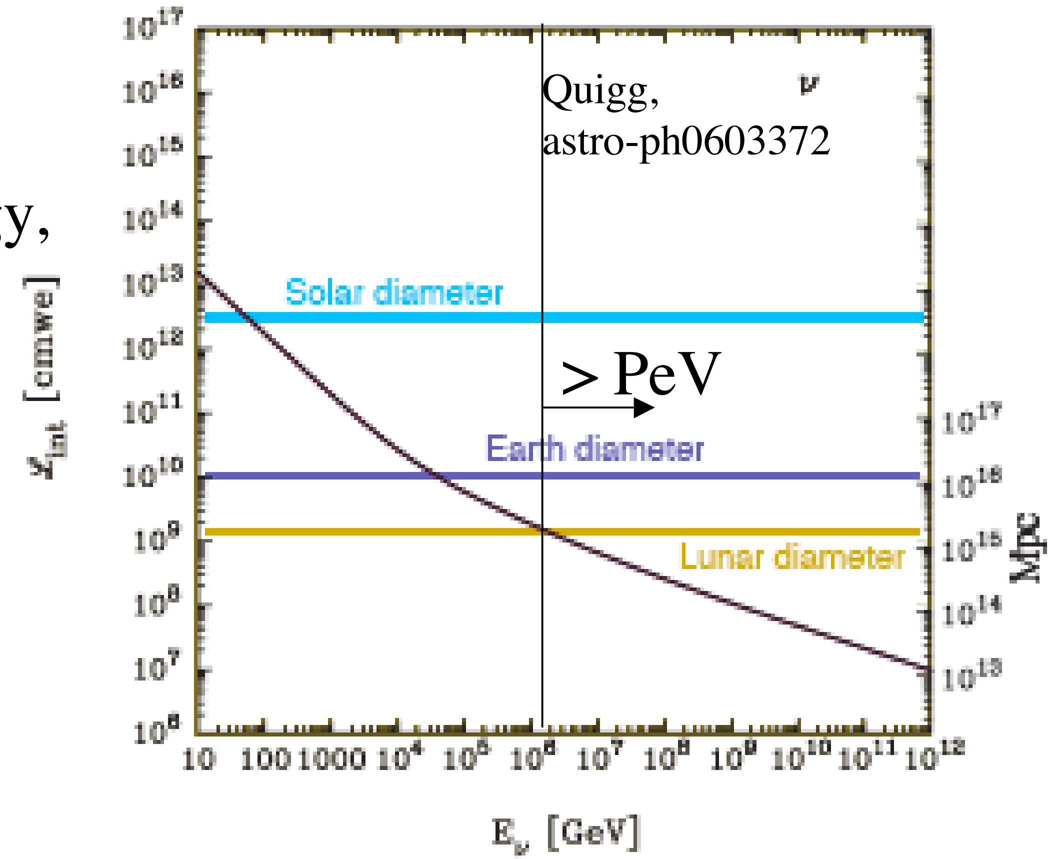


But are they out there? How to find them?

Strategy:

Look for their interactions in the earth...

The higher the energy, the shorter the interaction length!



And the higher the energy, the bigger the boom...

ν_τ CC: produces a "double bang" signature:
the CC interaction first (hadronic shower)
the τ decay second (also looks hadronic)
the exiting τ travels a distance of $50\text{m} \times (E_\tau/\text{PeV})$

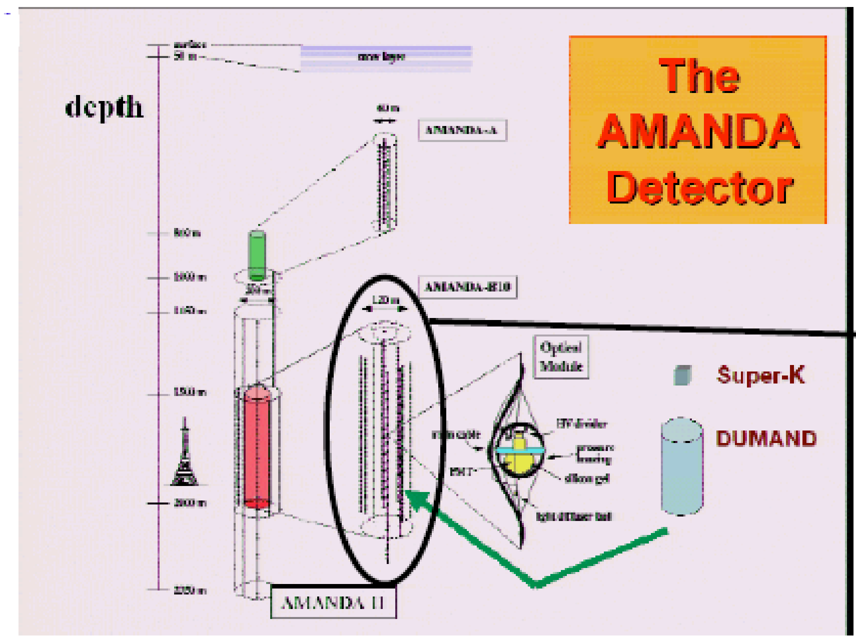
ν_μ CC: muons pair produce along the path, with
dE/dx roughly proportional to energy

ν_e CC: produce an electromagnetic shower

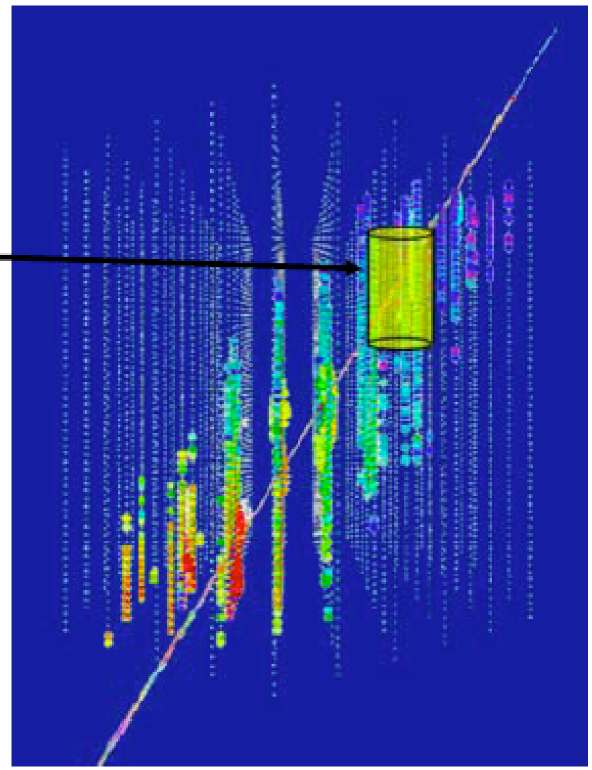
Detectors have to cover enormous distances.
Two types are feasible...

Cerenkov detectors in a large very clear medium...

Like ice in Antarctica:



IceCube

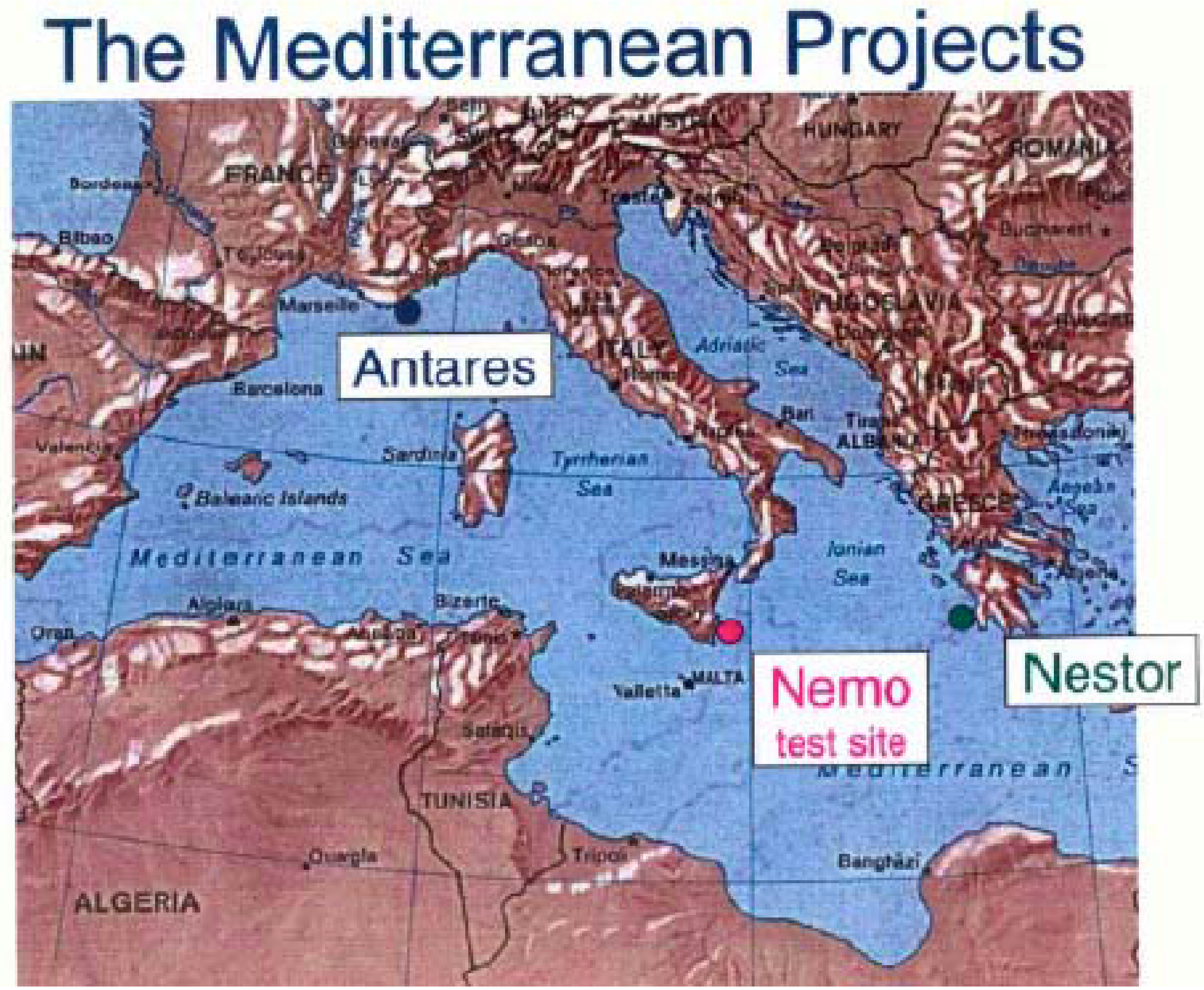


Which has the difficulty of allowing installation only in the summer season
(But shifts are -- literally -- very cool!)

...Or sea water

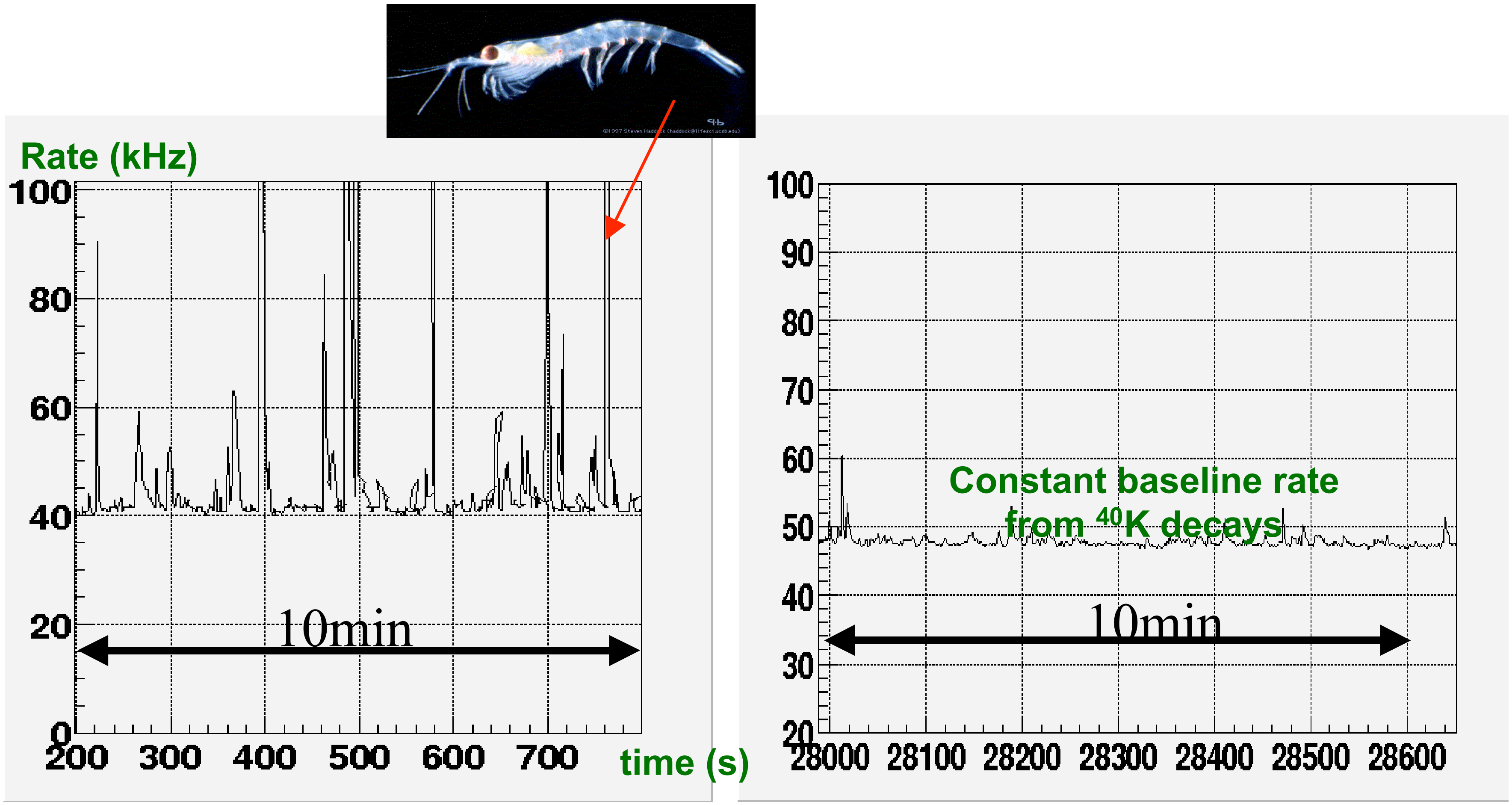
Janet’s opinion:
Sea water has
major drawbacks...

- Potassium
- Bioluminescence
- Ocean currents
- Opaque structures
  for tubes
- Shorter light
  attenuation length

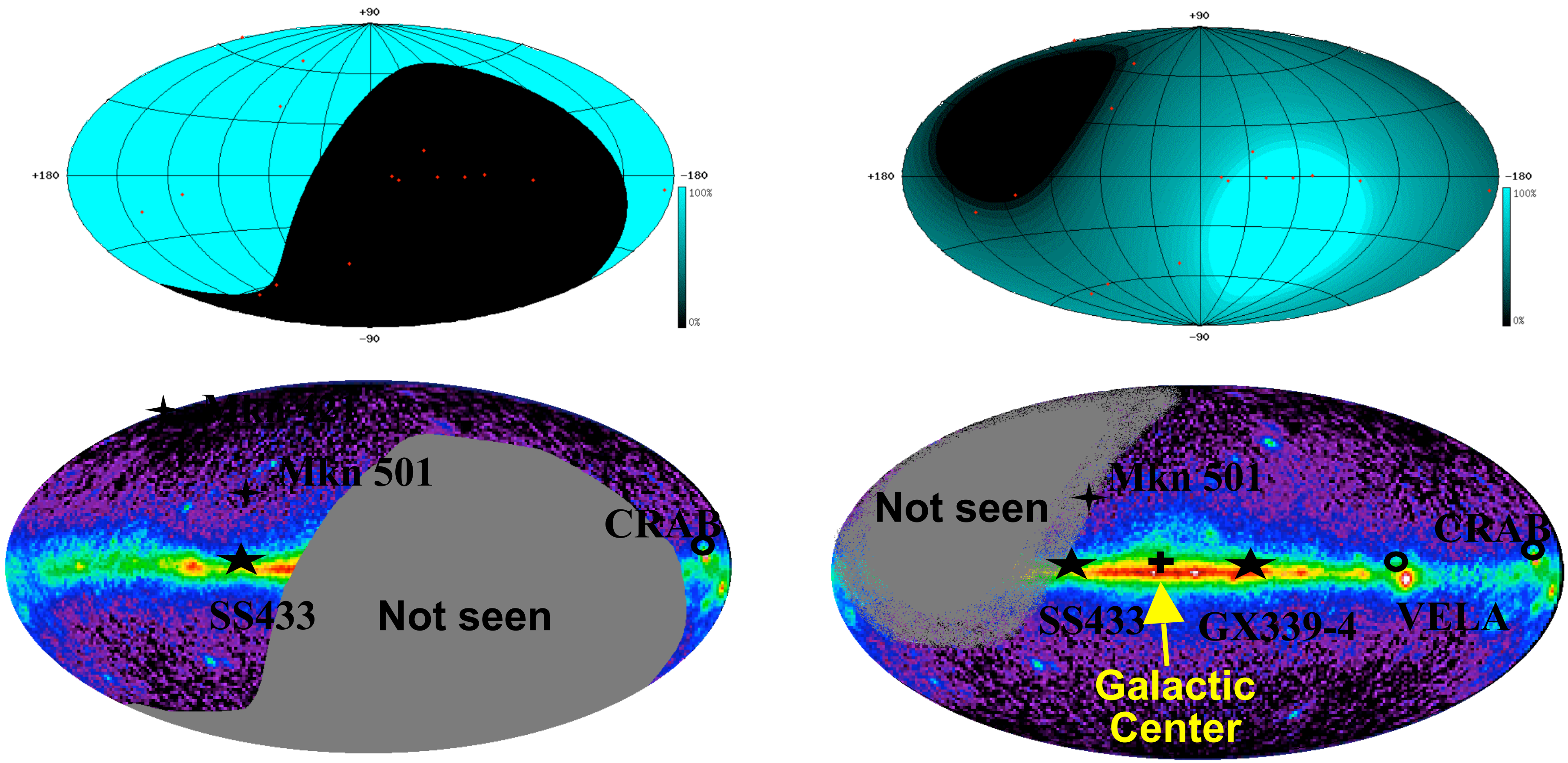


... but it is hard to beat the location!

Antares has deployed prototypes and measured backgrounds:



For astrophysics, the two locations are complementary:

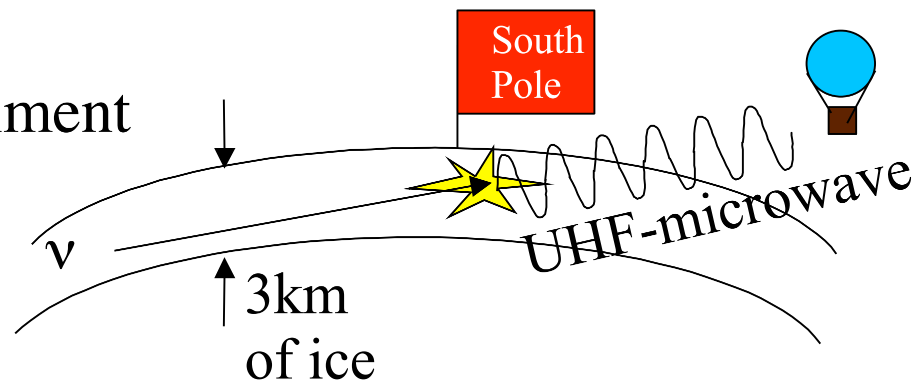


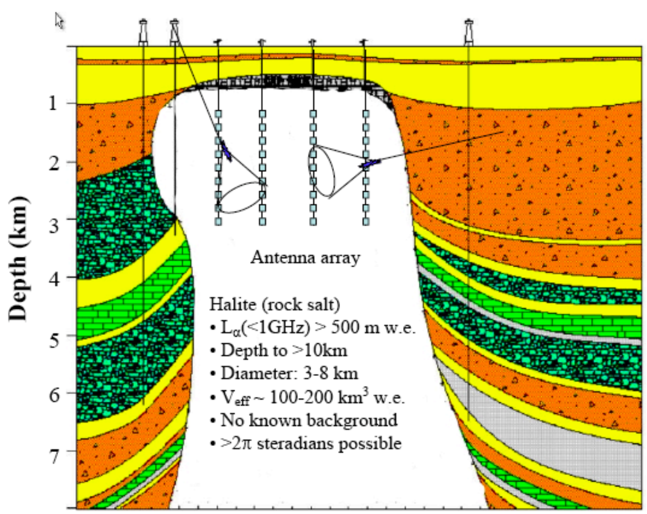
South Pole **Mediterranean**

The second method to observe UHE neutrinos:
Radio/microwave detectors....

The charged particles in the showers are producing electromagnetic waves which can be detected

For example:
The Anita Experiment using ice





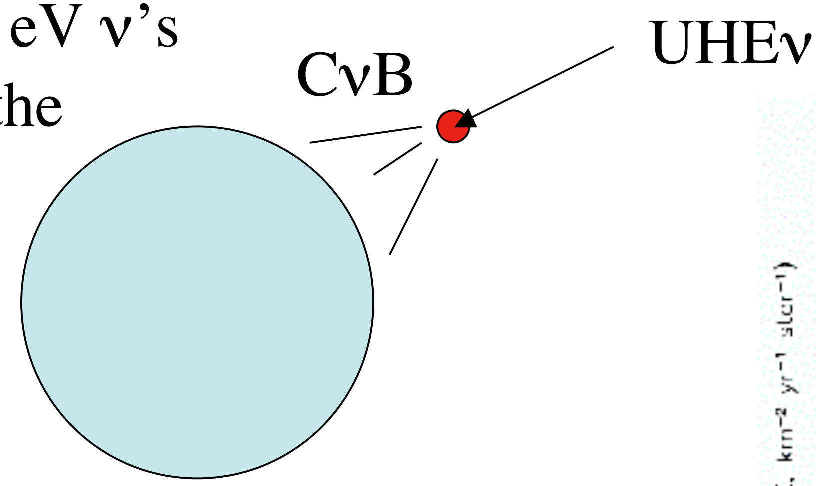
Or the proposed SALSA experiment, which will use a salt dome

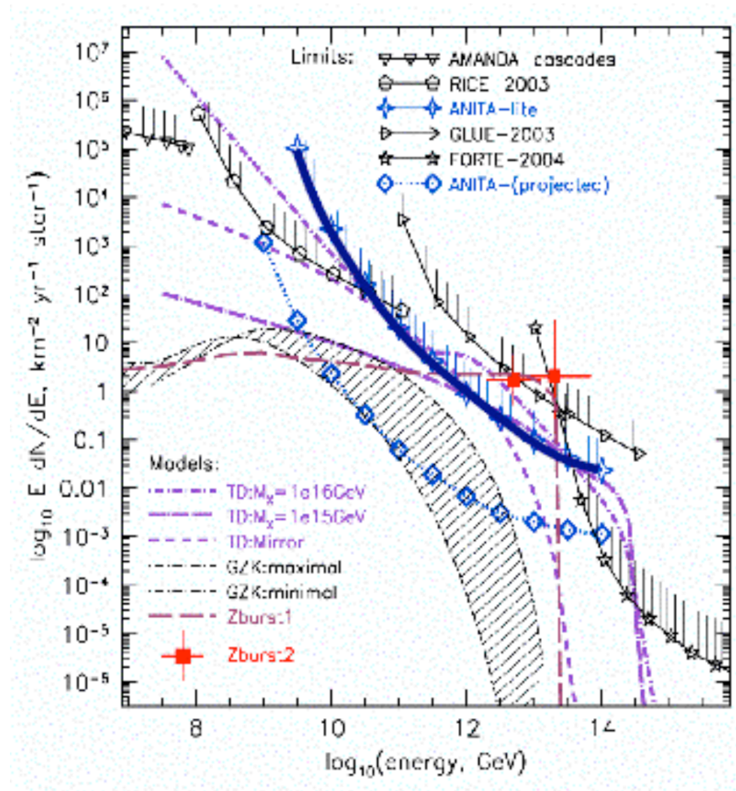
Since this is frontier physics,
even a short-run experiment can do a lot!

Anita-lite has already ruled out "Zburst Models"
ultra-GZK ν + CνB $\rightarrow$ Z $\rightarrow$ UHECRs

Kusenko & Weiler,
hep-ph/0106071

needs ~1 eV ν's to make the cross section work out



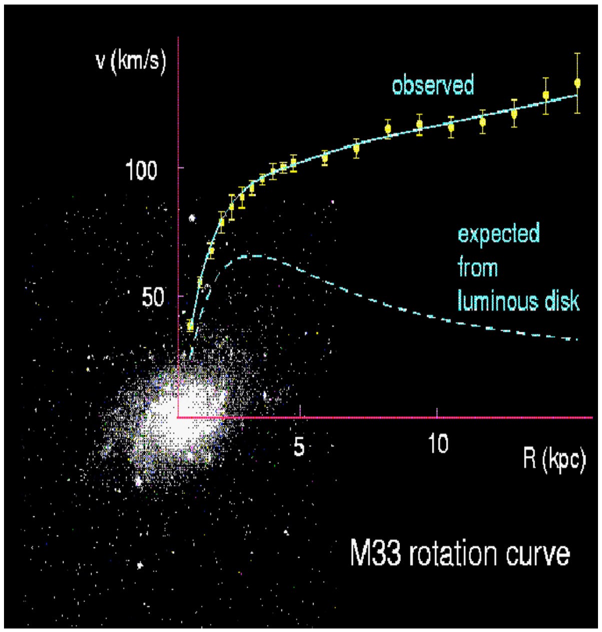


Prototype for the Anita Experiment,
with 18.4 days of flight time

Dark Matter

Not your Standard Model Neutrino!

Characteristics:



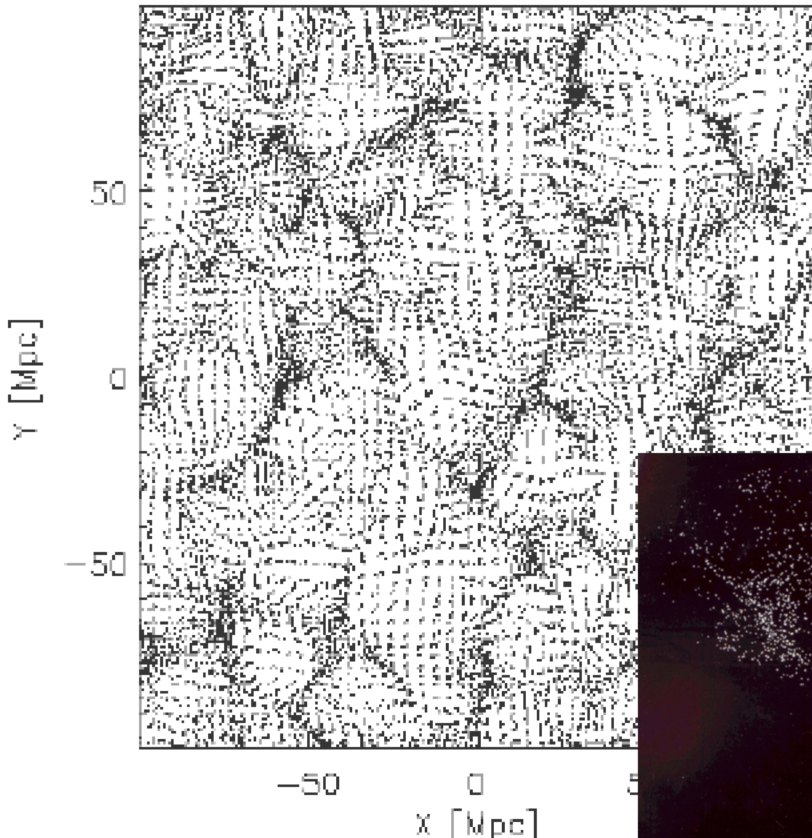
- ✓ Does not “shine” in the visible (or other) domain
- ✓ Present today (must not decay)
- ✓ Does not affect nucleosynthesis
- ✓ No sign of interactions (yet)

  → weaker than strong or EM forces.

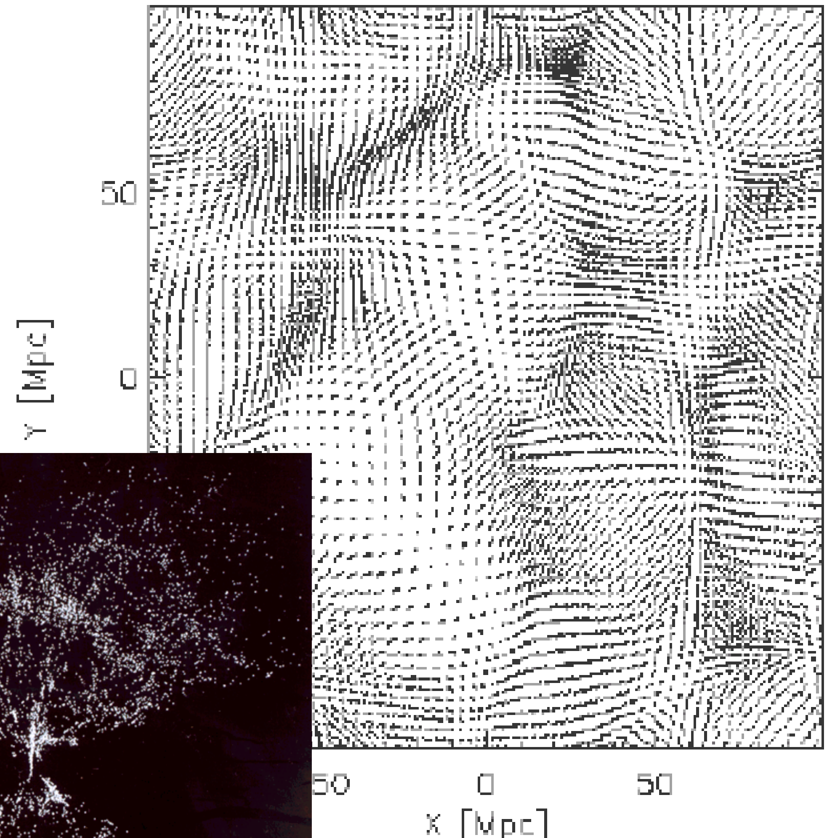
  worry: maybe it doesn’t interact except via gravity?

It’s not entirely hot dark matter (v>0.99c)....

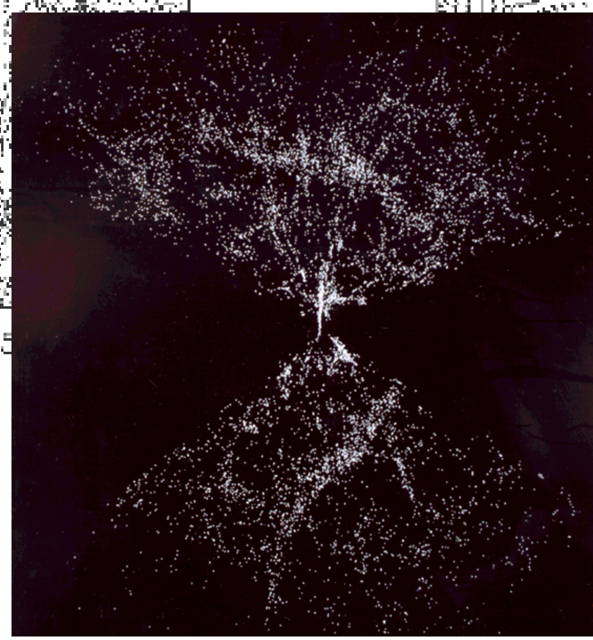
Simulated Structure
given CDM

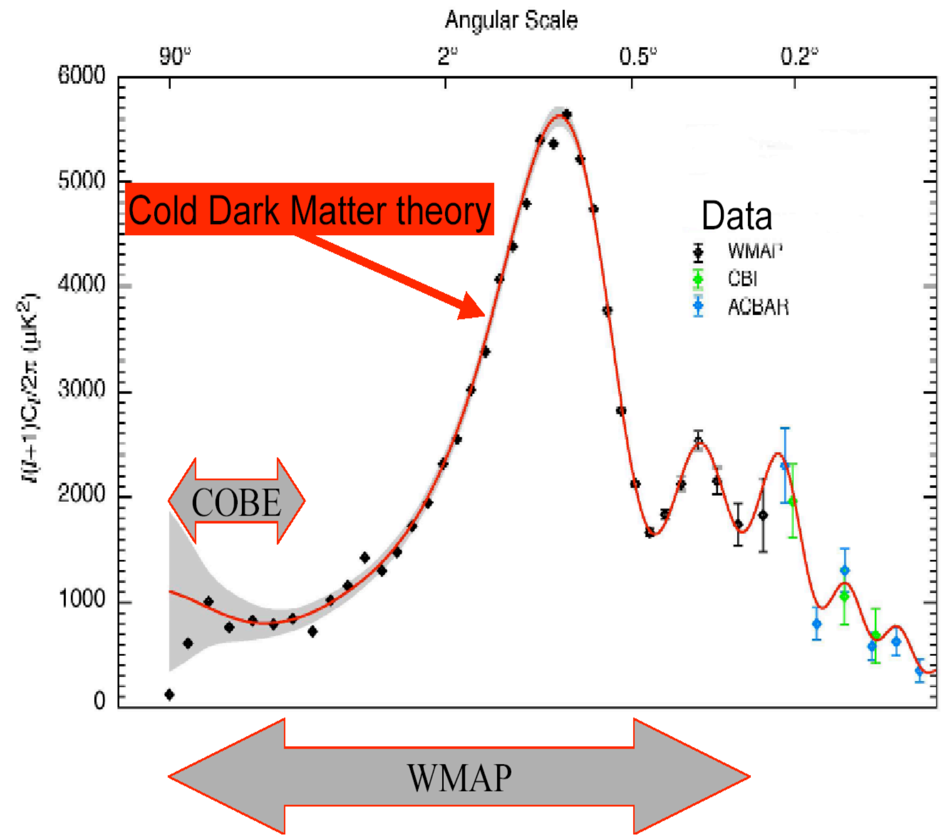


Structure given
HDM



Our universe...





The CMB power spectrum is well-fit if you include one non-relativistic, non-interacting extra particle (and pure HDM does not fit)

So it's not your Standard Model neutrino -- That would be HDM

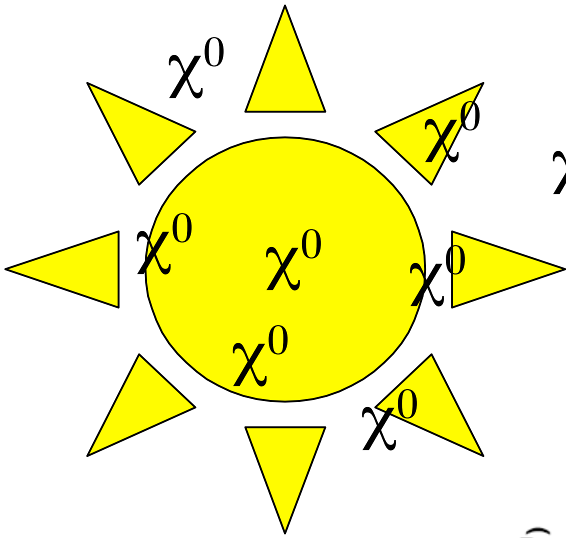
CDM candidates:

- Machos (massive compact halo objects) -- small percentage
- Axions
- Things in extra dimensions
- Non-standard neutrinos (WDM)
- Neutralinos, aka WIMPs (~100 GeV)

... the much-discussed candidate

If it's not neutrinos,
what is it doing in this talk?

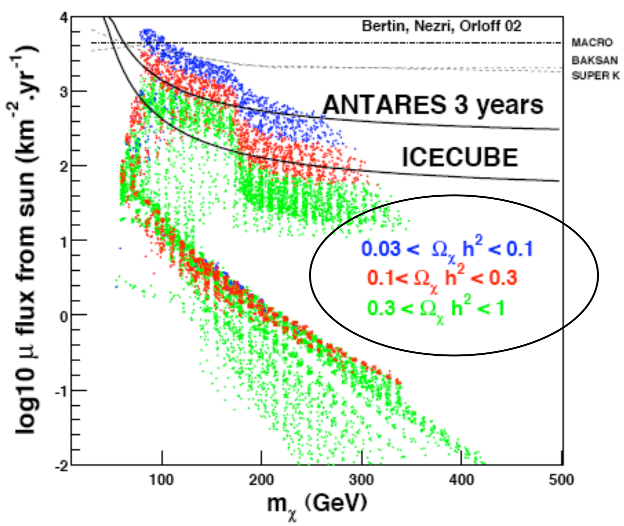
If it’s neutralinos,
the UHE neutrino experiments can do indirect detection!



$\chi^0\chi^0 \rightarrow$ quarks, leptons,
W, Z, maybe even H bosons

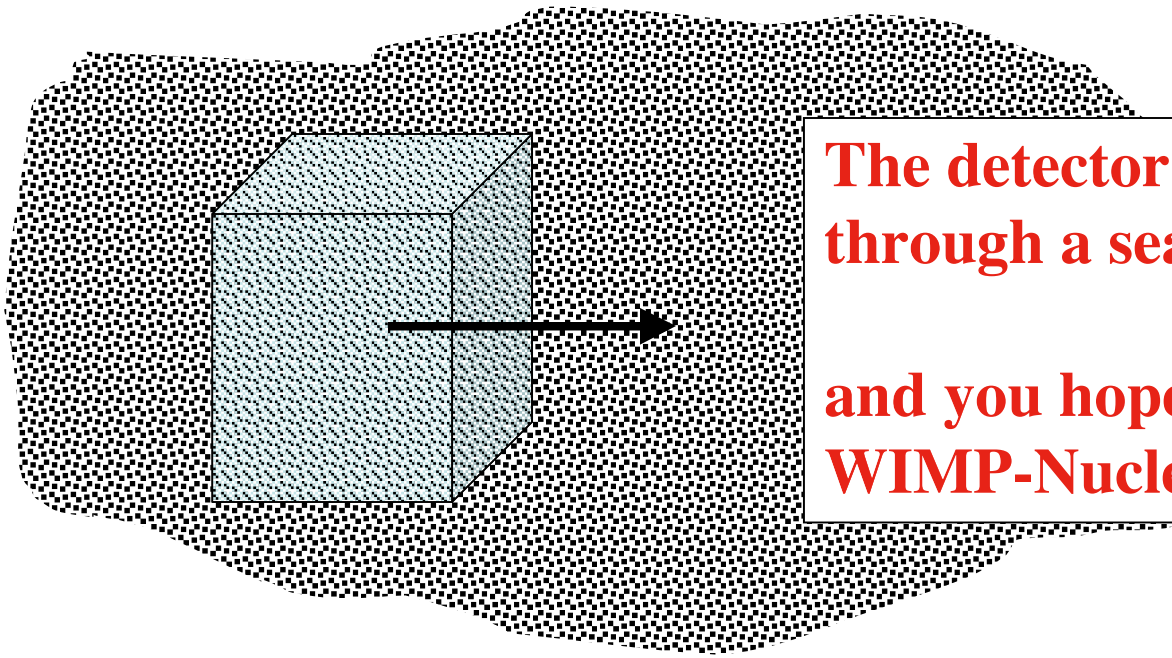
$\Downarrow$

Neutrinos!



some reasonable
models to fit the
cosmological data

Direct DM detection experiments
also have a lot of overlap
in technology with neutrino experiments!



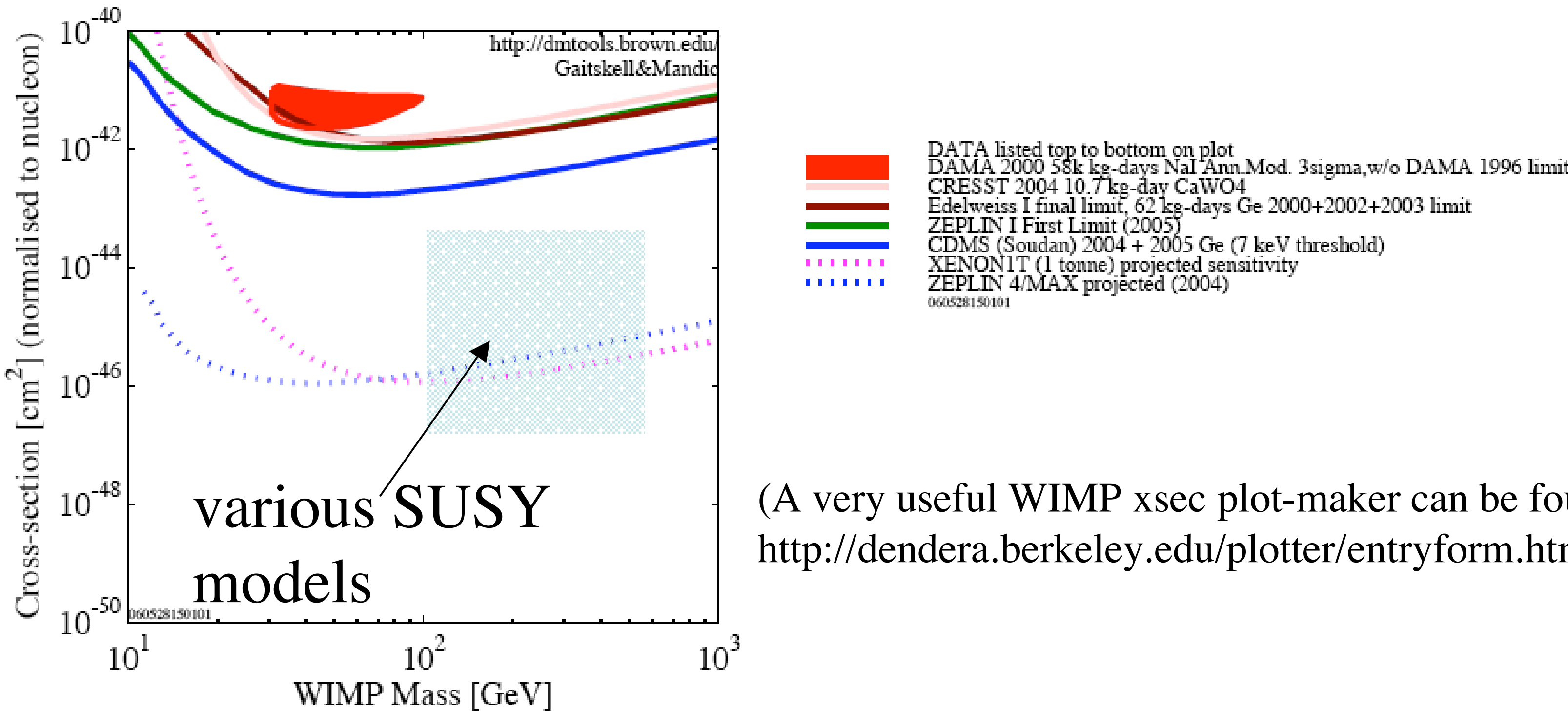
The detector is dragged through a sea of WIMPs

and you hope for a WIMP-Nucleon collision

The CM energy for the collision will be very small.
Recoil nucleons may have 10's of keV.
You need a detector with very low energy resolution,
and very low radioactive backgrounds

The noble gas (Neon, Argon, Xenon) technologies are especially relevant to neutrino studies....

Results and expectations for Zeplin and XENON (Xenon):

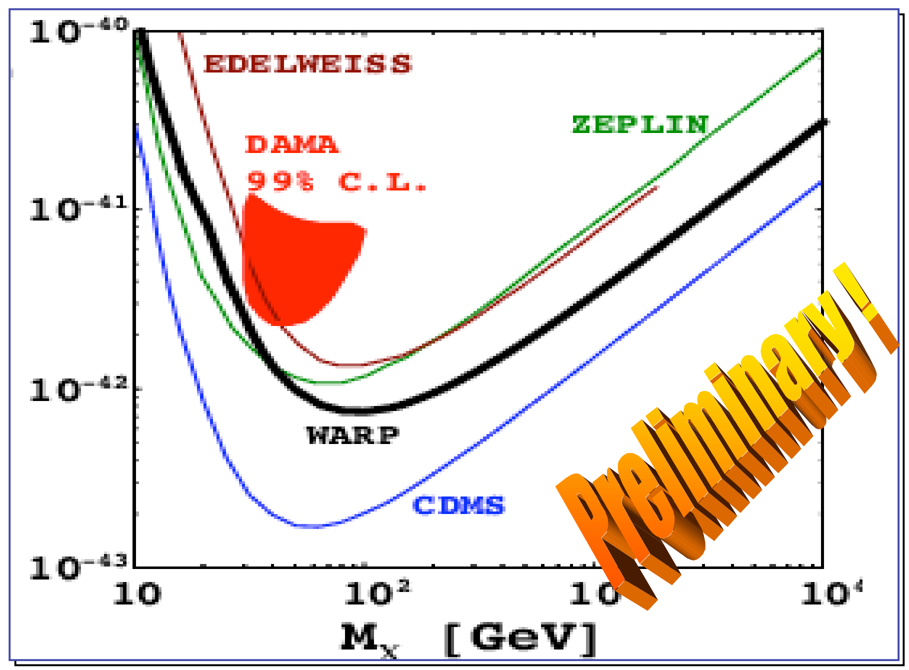


(A very useful WIMP xsec plot-maker can be found at http://dendera.berkeley.edu/plotter/entryform.html)

An exciting new development: DM searches with LAr
WARP, DEAP and CLEAN-LAr

This technology is turning out to be much nicer than expected!
Very high scintillation light yields for Nuclear Recoils
Rejection of ^{39}Ar β-decays is ×10 better than required

The WARP prototype results:



from J. Pandola, talk at CryoDet, March, 2006

Janet’s opinion (apology):

The AstroCosmoNuclearParticle field is just too wide and diverse in its goals for me to do it justice!

Here I have pointed out three experimental questions that interest me.

But I really urge you to look at the report of the APS astro-cosmo working group

Neutrino Opportunities

But Wait! There's More!

But by placing experiments
in the context of Today's Questions,

I've missed the chance to point out
tools available for your use,
as you pose Tomorrow's Questions...

"Neutrino tools" available to you
in the next decade...

New Beams in the Next Decade:

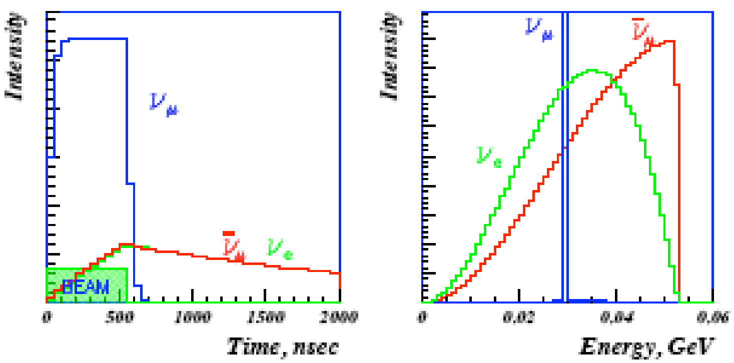
The lack of hadron beams is a problem.

The main source will be JPARC in Japan

So we need to get creative....

- A highly under-recognized beam that is very nice: SNS

Beautiful time-structure, monoenergetic ν_μ's starts at 1 MW....



- Other interesting dumps:

  NuMI -- there is a monoenergetic line from K-decays

  LHC (anyone interested in ν_τ's?)

New Detectors in the Next Decade:

The trick is to find the multi-hundreds of kton,
multi-purpose detector.

Right now the chief competitors are:

Water Cerenkov

(scintillator oil would be vastly too expensive,
can we make water-based scintillators work?)

LAr -- not yet proven at the kton scale, much less Mton

Maybe we need to get smarter technology!

New Ways to Access Neutrino Properties
in the Next Decade:

Traditionally we have used neutrino beams.
But the LEP invisible line-width example shows not all neutrino experiments need to see neutrinos.

LHC is turning on, what neutrino physics will you do with it?

If we can build an experiment to look for the invisible decay of positronium to BR~10^{-10} (maybe eventually to 10^{-11})... what exotic neutrino models can we test?

Ideas Welcome

New Labs in the Next Decade:

The goal is to build an underground lab in the U.S.

The choice has been narrowed to two competitors

This lab joins SnoLab, Kamioka, Gran Sasso and Frejus

The door is open to all kinds of interesting questions!
What new physics so you want to access by going underground?

Conclusion

It's a big nu world out there.